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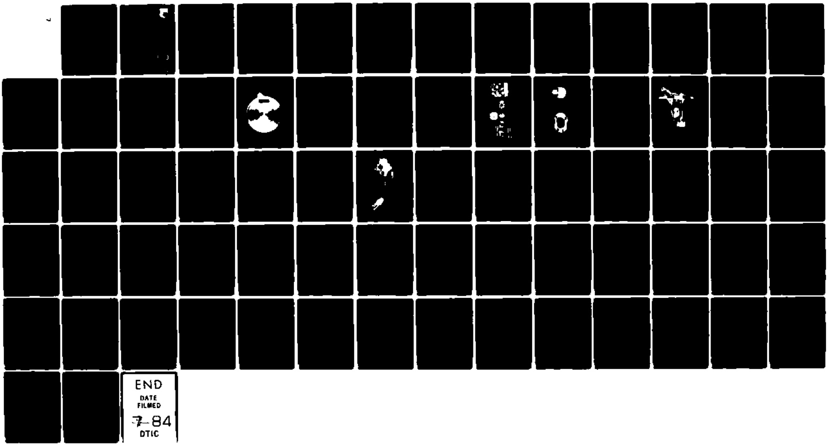

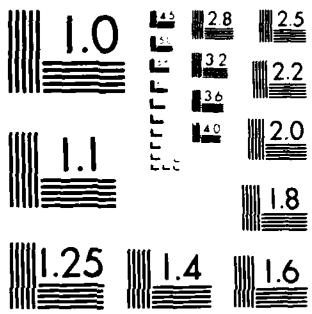

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AFWAL-TR-83-2065

EFFECTS OF MICRONIC FILTRATION ON TURBINE ENGINE LUBRICANT DEPOSITION

SOUTHWEST RESEARCH INSTITUTE
6220 CULEBRA ROAD
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OCTOBER 1983

FINAL REPORT FOR PERIOD 15 AUGUST 1980 - 15 AUGUST 1983

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This technical report has been reviewed and is approved for publication.

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The effects of micronic filtration on deposit forming characteristics of turbine engine lubricants were investigated, employing a hot-wall deposition test rig. The test-oil sump of the rig was modified with a wear-metal generator and for filtration tests, a filter housing was installed in the test lubricant pressure line. Without filtration, 15 μm filtration and 3 μm filtration tests were performed. Ten MIL-L-7808 or MIL-L-7808 type lubricants were evaluated under six different test conditions. Accordingly, a special

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20. ABSTRACT (CONT'D)

test method was used to study the effect of micronic filtration on deposition of the lubricants both with mild steel wear generation and without wear generation. Also, the effects on both kinematic viscosity and neutralization number of the test lubricants were determined and are presented. A direct calculation of wear-metal generation was provided by weight-loss measurements of the mild-steel wear coupons mounted below the lubricant level in the sump. Also, the concentration of iron in samples of the test lubricants taken during testing was determined by energy dispersive X-ray fluorescence and these results are presented and discussed.

Ferrographic analyses as well as COBRA results on selected lubricant samples and 3 μm filters sent to Air Force Wright Aeronautical Laboratories (AFWAL) are presented.

A statistical analysis of the three response variables, namely deposit rating, viscosity increase and neutralization number change, by analysis of covariance was performed. From this analysis there is clearly a significant difference between deposit rating averages when no filtration is present as opposed to filtration. On the other hand, while average deposit ratings were slightly higher with 15 μm filtration as opposed to 3 μm filtration, there was no significant difference between the two. The analysis results for viscosity increase and neutralization number change showed no interaction between lubricant and filter. Also, no significant differences existed among the viscosity increase- and neutralization number change--means for the three filtration conditions.

FOREWORD

This report was prepared at Southwest Research Institute (SwRI) under Contract F33615-80-C-2034, Project No. 3048. The work was monitored by the Lubrication Branch, Fuels and Lubrication Division, Air Force Aero Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio. The project engineer was Mr. L.J. DeBrohun, AFWAL/POSL.

The report covers the period August 15, 1980 through August 15, 1983. This report was submitted by the authors in August 1983.

The authors gratefully acknowledge the contributions and assistance provided by Messrs. G.P. Lee, J.E. Wallace, S.D. Ott and M.R. Gass in build-up and operation of the test facility and also laboratory determinations.

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SECTION I

INTRODUCTION

Objective and Scope

As specified in the Description/Specifications of Contract F33615-80 C-2034, the objective of the proposed program was to determine the effects, positive or negative, of fine filtration on the deposit forming characteristics of qualified and experimental turbine engine lubricants.

In order to accomplish this objective, four major phases are outlined as follows:

Phase I - Select a suitable test or tests that can accurately and inexpensively rate the deposit forming characteristics of synthetic turbine engine lubricants, and that can be modified to accept suitable filters in the test rig plumbing.

Phase II - Select filtering techniques, considering both membrane and cartridge type filters. Also determine necessary plumbing schemes and sampling techniques to accommodate filtration.

Phase III - Test lubricants (10 to 12 each) with and without fine filters to determine a deposit baseline and filtering effects. Analyze used lubricants and deposits.

Phase IV - Perform analysis and evaluation of data generated under Phase III.

As will be discussed later in Section II of this report, Phase I involved the selection of a test employing a hot-wall deposition rig which has been modified with a wear-metal generator and filtration capabilities to accomplish the necessary tasks outlined. The basic hot-wall deposition rig was designed, developed and employed on previous programs[1,2]* and is subsequently

* Superscript numbers in parenthesis refer to the References included in this report.

described in Section III of this report. The selection of suitable filters for this program was made through contacts with three major turbine engine manufacturers and one filter manufacturer and will be discussed in more detail in Section II of the report. Ten test lubricants supplied by the Air Force Wright Aeronautical Laboratories (AFWAL) and described in Section III, were tested both with and without filtration in accordance with the scope of the program. Finally, analysis and evaluation of the data generated during testing was performed and is presented in Section IV. Hot-wall summary data for all of the tests are presented in the Appendix of the report.

Background

The United States Air Force (USAF) continues to have an interest in improving the performance of existing and future propulsion systems. One area that is of utmost concern is the wear in turbine engines as caused by contact of moving surfaces such as rotating bearings, gears, seals, etc. Since the lubricant is designed to both lubricate and cool these components it will inherently serve as carrier of wear debris and deposits, and distribute same throughout the oil-wetted system. This debris can contribute to accelerated wear and may ultimately lead to early failure. In an effort to minimize or eliminate this, filters have been incorporated in the circulating lubrication systems and more recently the trend has been toward very fine (small pore size) filtration. Although the use of improved turbine engine lubricant filtration offers the possibility of improved performance as associated with wear, deposition, jet plugging, etc., the effects of fine filtration are not known. Previous research and testing pertaining to lubricant degradation has been primarily involved in the development of techniques for measuring deposition. The intent of this program was to determine if existing lubricant deposition characteristics are altered by fine filtration. Toward this goal the planned effort was to evaluate the effects/interactions of micronic filtration and wear-metal particulates on the deposition characteristics of the ten lubricants. Each lubricant was evaluated at two levels of wear-metal generation, i.e., with and without, and three levels of filtration, i.e., none (screen), 3 μm absolute, and 15 μm absolute.

SECTION II

TEST AND FILTER SELECTION

General

The criteria for selecting the particular test and filters employed in this program are discussed below. After presentation of this information, the test rig and its operation are discussed in detail in the following section of the report. Also included is a description of the ten test lubricants employed during the program.

Test Selection

A review of available test devices, and new concepts thereof, was p formed to permit selection of a suitable test. Primary criteria appliec .ı the selection process included accuracy, performance cost, and the requir ment for incorporation of micronic filters and a wear-metal generation device. It was decided that the hot-wall deposition test represents the optimum choice on the basis of these selection criteria. The lubricant system was readily adaptable to incorporation of in-line filters. Furthermore, the accuracy of the test has been demonstrated[2] by a pooled standard deviation for deposit ratings of 8.1. This statistic was calculated for 46 determinations on several test lubricants. The value was considered to be indicative of reasonable test precision in view of the fact that the results were obtained with four separate test rigs in random sequence over a period of 4 years.

Earlier work discussed above also used an integral wear-metal generator and the concept was thought to be adaptable to this program. However, a separate wear-metal generator (separate from the test-oil pump) and associated drive system was planned and subsequently used to permit greater flexibility in the test facility.

Filter Selection

The selection process for suitable filters was made through contacts with three of the major engine manufacturers and one filter manufacturer,

Aircraft Porous Media (APM), a prominent vendor for aircraft engine main oil filters. As a consequence of this survey, APM paper elements rated at 0.9/3 μm and 10/15 μm were selected. The 3 μm elements are currently being used on some engines and it is not expected that any finer elements will be in use for the foreseeable future. The 15 μm elements were selected because there was some consensus that this size would be in general use on many future engines.

The following comments obtained during the survey are presented for record. Filter ratings cited are absolute or nominal/absolute.

General Electric. Most of GE's experience has been with recleanable type filters; however, they are converting to disposable elements for many engines. It was stated that GE's T700 engine employs a 3 μm disposable filter. The J79 and most commercial type engines utilize a 46/74 μm metal filter. This filter was originally used on the CF6 engine but is being converted to a 10/15 μm disposable element. Several small helicopter engines supplied by GE employ a 25 μm filter. It was indicated that a 10/15 μm element would probably be a typical rating for future GE engines. APM is the primary filter vendor used by GE.

Detroit Diesel Allison. Allison's T56 engine uses separate 115 μm filters for the reduction gearbox and the power section. A 20 μm element also serves as an external scavenge oil filter. The filters may be metal or paper. The military version of the T63 engine uses an 81 μm filter; however, customers of the commercial version have incorporated external filters rated at 3 or 10 μm. Field replacement filters and new production engines of the TF41 use a 30 μm primary filter (paper) and a 140 μm secondary filter (metal). A 25 μm metal filter is used in a differential pressure switch line. APM and Purolator appear to be the major vendors for Allison.

Pratt & Whitney Aircraft-Connecticut. Although they are not convinced that micronic filtration is necessary for normal conditions, i.e., paved runway or carrier operations, P&WA-Connecticut expects that 15 μm will be the probable filter rating for future engines. APM is the primary vendor for P&WA-C.

Pratt & Whitney Aircrart-Florida. P&WA at Florida was solicited for their input since the facility is the primary supplier of P&WA military engines, as opposed to the Connecticut plant which is primarily concerned with commercial engines. Personnel indicated that APM is the major supplier of main oil filter elements. Most engines are equipped with throwaway elements rated in the range of 5 to 17 μm absolute, some models utilize a 70 μm cleanable element. It was stated that 3 μm elements are used only on some experimental engines. For future engine designs, it was estimated that 5 μm filters would probably be favored. P&WA Florida personnel indicated that they believed micronic filtration of the lubricant was significantly beneficial in reducing wear and extending engine life.

Aircraft Porous Media. APM stated that the following filter elements were in use: 0.9/3 μm on the T700 and T63 engines; 10/15 μm on the TF30, on F-14 aircraft; and 10/30 μm on the J52 and some TF30 engines. APM also commented regarding filter element flow densities, expressed as gpm oil flow per square foot of filter surface. Normal flow densities for turbine engine lubricant systems are in the range of 407-1222 $\ell/min/m^2$ (10-30 gpm/ft^2). The minimum recommended is 41-204 $\ell/min/m^2$ (1-5 gpm/ft^2). Below this range, it was stated that particles will be adsorbed by the filter media fibers. This results in an unrealistic (relative to the filter rating) particle distribution downstream of the filter.

On the basis of information gathered, two element ratings were selected for use in this program. These were procured from APM. Using earlier terminology the two filter ratings would be described as 0.9 μm nominal, 3 μm absolute and 10 μm nominal, 15 μm absolute. Current filtration technology no longer recognizes the use of such ratings since values vary with manufacturer's interpretations. Presently, the preferred criterion of filter capability is the beta ratio (β_x) defined as the ratio of the number of upstream particles larger than x μm to the number of downstream particles larger than x μm, for a given fluid volume. As an illustration, a β_3 of 100 signifies that if 100 particles of size greater than 3 μm enter the filter, no more than one particle of size greater than 3 μm will pass the filter for an equal fluid volume.

For ease of identification and discussion, continued reference to the two elements as 3 μm and 15 μm will be used; however, it should be recognized that these designations have little technical basis. For example, APM has supplied beta ratio plots for the two elements as shown in Figure 1. It is of interest to note that the 3 μm element has a β_3 of 500, while the 15 μm element shows a β_{15} of 1000.

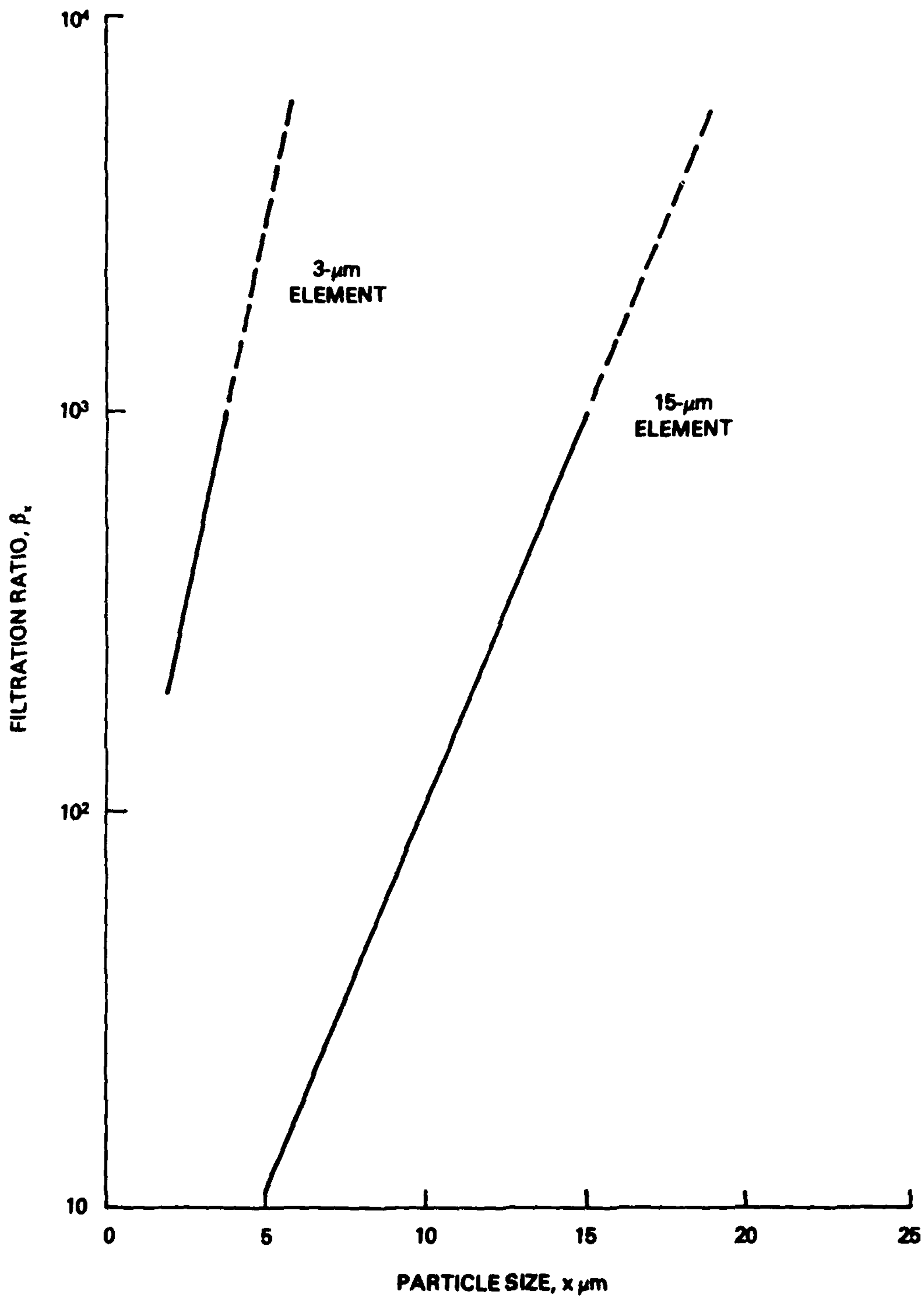

FIGURE 1. VENDOR'S ESTIMATED BETA VALUES FOR TEST FILTER ELEMENTS

SECTION III

TEST EQUIPMENT AND LUBRICANTS

General

The test equipment used in making the deposition evaluations contained herein consists of a vertically mounted hot-wall test specimen attached to a specimen housing; one side of the hot-wall specimen surface is subjected to a lubricant fog, while the opposite side of the hot-wall specimen surface is in direct contact with a heating fluid which is maintained at predetermined temperatures. A recirculating test-oil system containing a test-oil pump and wear generator, and adaptable to a filter housing and sampling valves is also part of the equipment. A simple laboratory air supply system completes the necessary equipment for the hot-wall deposition rig.

The hot-wall deposition rig was designed to simulate, as closely as possible, the actual engine operating conditions with regard to oil dispersion, flow rate, and temperatures in the area surrounding the No. 2 rear bearing support of the J57 turbojet engine. A No. 2 rear bearing support from a J57 engine is used as the test specimen in the hot-wall deposition rig. The general configuration and principal dimensions of this engine part, modified to include an integral fluid-heating tank have been shown and discussed in previous reports.[1,2] A photograph showing one of the actual test-specimen deposit surfaces employed in this work is shown in Figure 2.

Two hot-wall deposition rigs were used during this program. The following paragraphs describe the hot-wall deposition rig, the wear generator and wear coupons, the operating procedure, the deposit rating procedure, and trace-metal analysis procedure. Immediately following these descriptions a tabulation of the lubricants employed and supplied by AFWAL is presented.

Hot-Wall Deposition Rig

A schematic of the hot-wall deposition rig is shown in Figure 3. The hot-wall spray chamber consists of a stainless steel cylinder flanged at

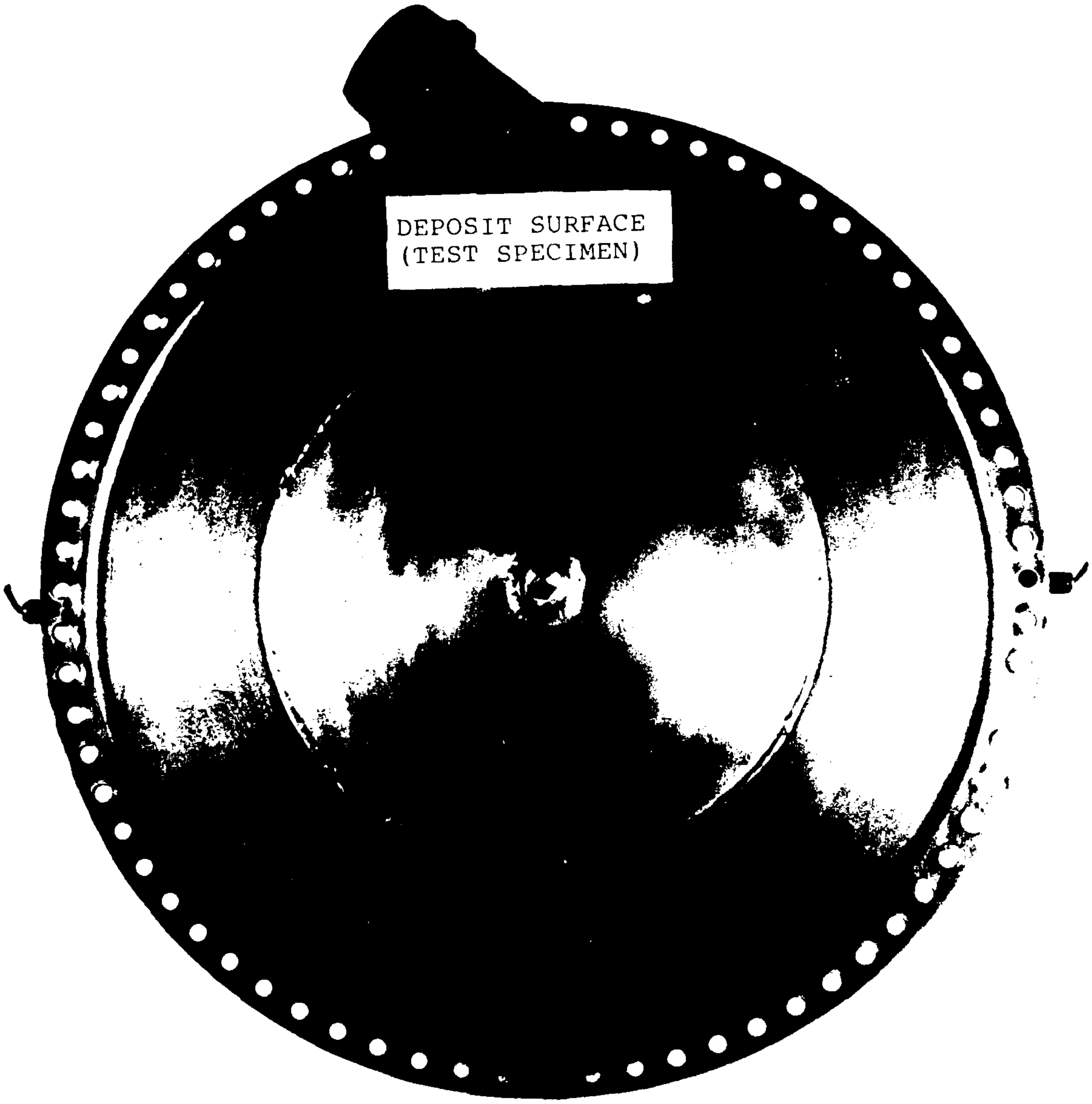

FIGURE 2. CLEANED DEPOSIT SURFACE PRIOR TO TESTING

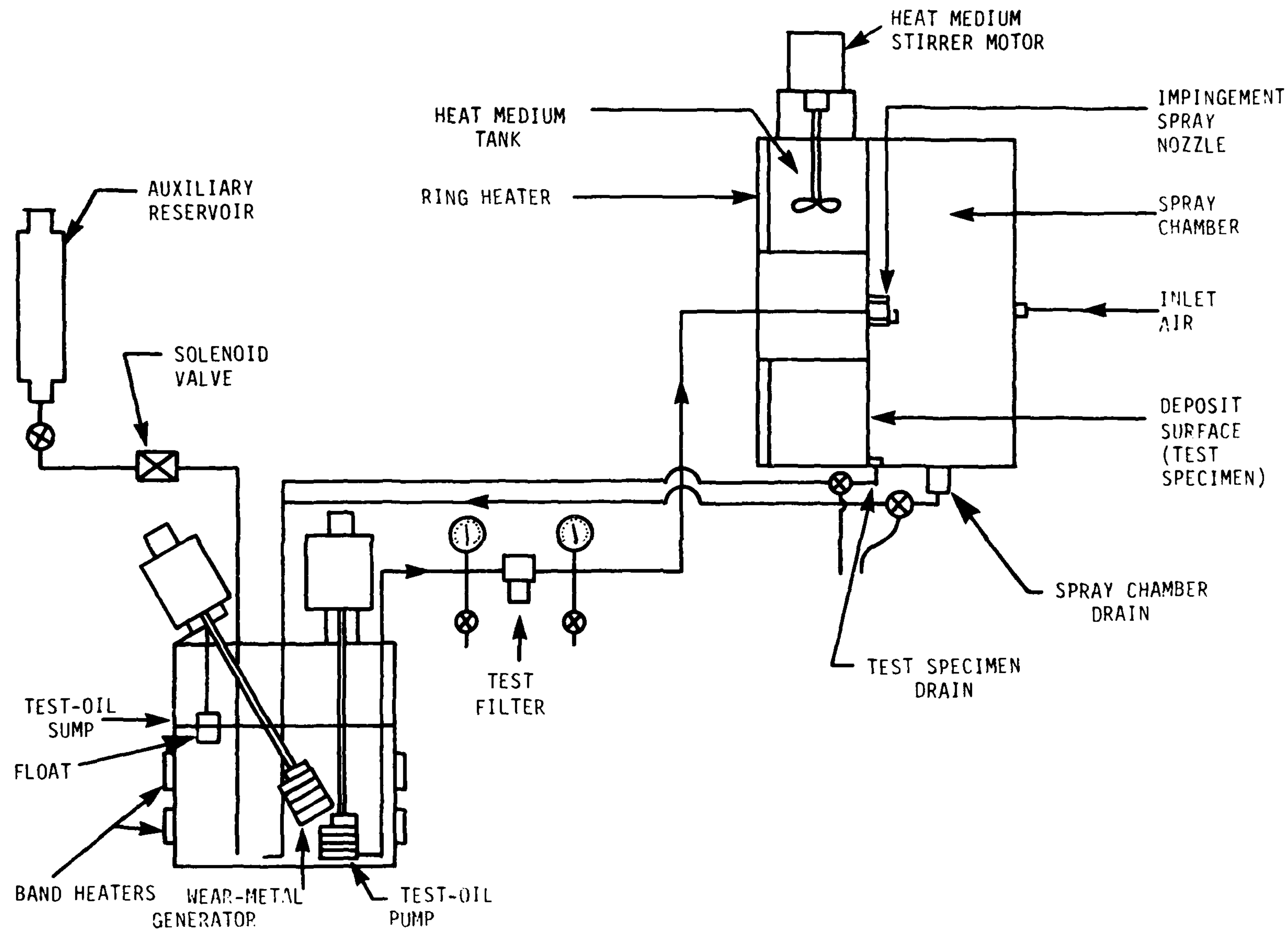

FIGURE 3. SCHEMATIC OF HOT-WALL DEPOSITION RIG

the end that attaches to the deposit surface (test specimen) and closed at the opposite end except for the inlet-air connector. The deposit surface is indirectly heated by means of a heat-medium tank. The fluid used in the integral heat-medium tank is a reclaimed 5P4E polyphenyl ether. The fluid is heated by a 4,000-watt ring heater pressed against the tank wall opposite the hot-wall deposit surface. Agitation of the heating fluid by means of a stirrer inserted through the tank opening improves the uniformity of temperature throughout the tank.

The test lubricant enters the spray chamber through an impingement spray nozzle which directs the lubricant fog toward the front of the chamber, preventing direct contact of large droplets with the test specimen surface.

Provision is made in the spray chamber to separate the lubricant which contacts and runs off the test specimen surface. This is accomplished by forming a ridge inside the chamber along the inside diameter of the flange to which the deposit surface is attached. Lubricant running off the surface is trapped by the ridge and is diverted to a test specimen drain leading to a three-way valve. The balance of the lubricant draining from the spray chamber exits through a 100-mesh screen to a three-way valve.

Air at a controlled moisture content of 20 $\pm$ 2 mg of water per liter of air is admitted to the spray chamber at the inlet-air connector at a rate of 1.65×10^{-4} m^3/sec (0.35 cfm). The controlled air exits with the lubricant through the drains and back to the test-oil sump. The test-oil sump consists of a stainless steel container placed within a second container and having the exterior of the inner vessel coated with a 3.2×10^{-3} m (1/8-in.) thickness of copper to a height of 7.6×10^{-2} m (3 in.) from the sump bottom to better distribute the heat. Heat is supplied by two 800-watt band heaters. A positive displacement gear pump, designated test-oil pump, is mounted on the sump lid such that the pump is totally submerged in the test lubricant. This pump is located near the bottom of the sump. For all tests, a 100-mesh screen is attached to the pump intake. The lubricant pump is driven by a variable speed electric motor and a pressure control is incorporated in the lubricant pressure line to deactivate the pump in the event of a severe pressure excursion because of spray nozzle plugging.

To allow for unattended rig operation, makeup oil to the sump is dispensed automatically by use of a feedline with integral solenoid valve leading from an auxiliary reservoir. The solenoid is activated by a microswitch which contacts an oil level rod attached to a float within the test-oil sump. Measurements of the sensitivity of the oil makeup device indicate a test-oil sump volume control capability of 2,300 $\pm$ 25 ml.

Figure 3 illustrates the hot-wall deposition rig equipped with test-filter housing and associated pressure gages for determining pressure differential across the test filter. Valves for obtaining test-oil samples both upstream and downstream of the filter are also shown. The filters employed in the filter housing for various testing have already been discussed in a previous section of the report. For tests without filtration these equipment are eliminated from the plumbing arrangement and test-oil samples are taken from the spray chamber drain valve. Criterion used for changing the filter during filtration testing was when the differential pressure across the filter, as determined by the pressure gages, reached 6.2×10^5 Pa (90 psi).

Wear Generator and Wear Coupons

The wear-metal generator which operates totally beneath the lubricant level, but above the test-oil pump within the sump, is also shown schematically in Figure 3. The wear-generator components, as shown in Figure 4, include a modified test-lubricant pump, Zenith Model HPB-4647. The pump body is unmodified except for removal of the driven gear. The lower wear coupon rests directly on the pump body. The hub body sits over the lower coupon and the rotating drive plug is placed within the hub body. The upper wear coupon is next in line, followed by the hub top. The hub screws are then inserted to a fixed depth to achieve a measured compression of the load springs. The loading occurs only between the faces of the rotating drive plug and the wear coupons because the hub body thickness dimension has been machined undersized, and with diametrically opposed grooves for metal particles to escape. A typical wear track in a wear coupon is shown in Figure 5.

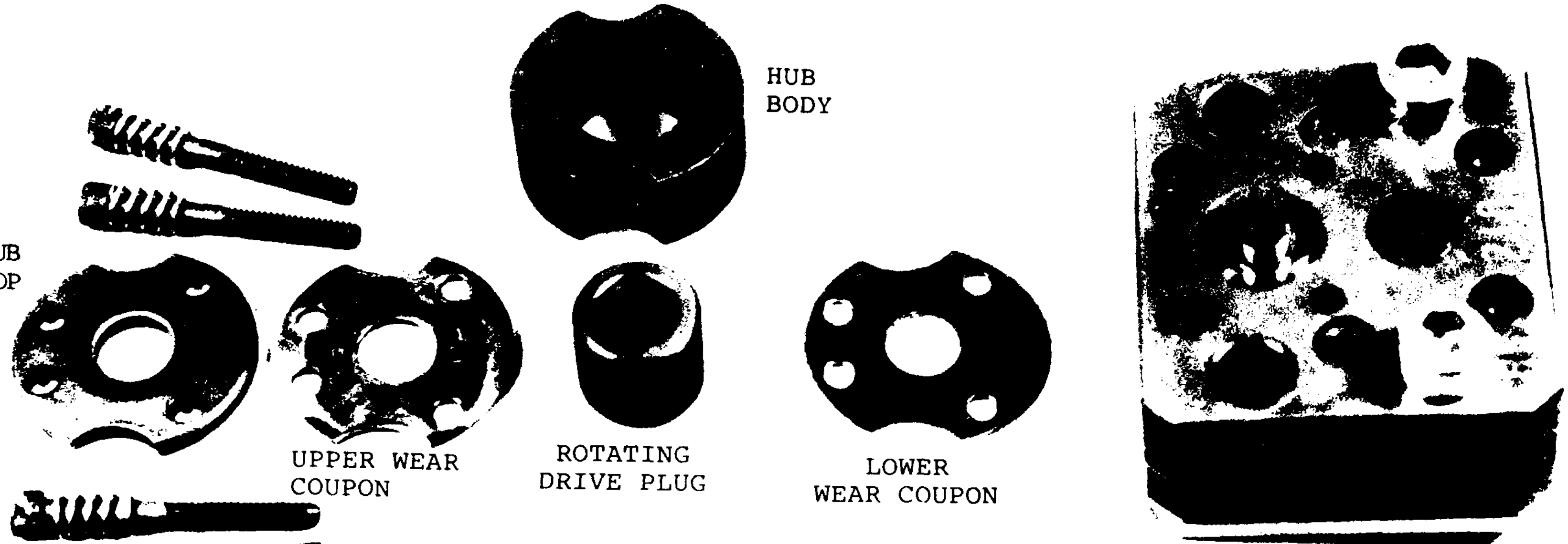

FIGURE [illegible]. COMPONENTS OF DESIGNED WEAR-METAL GENERATOR

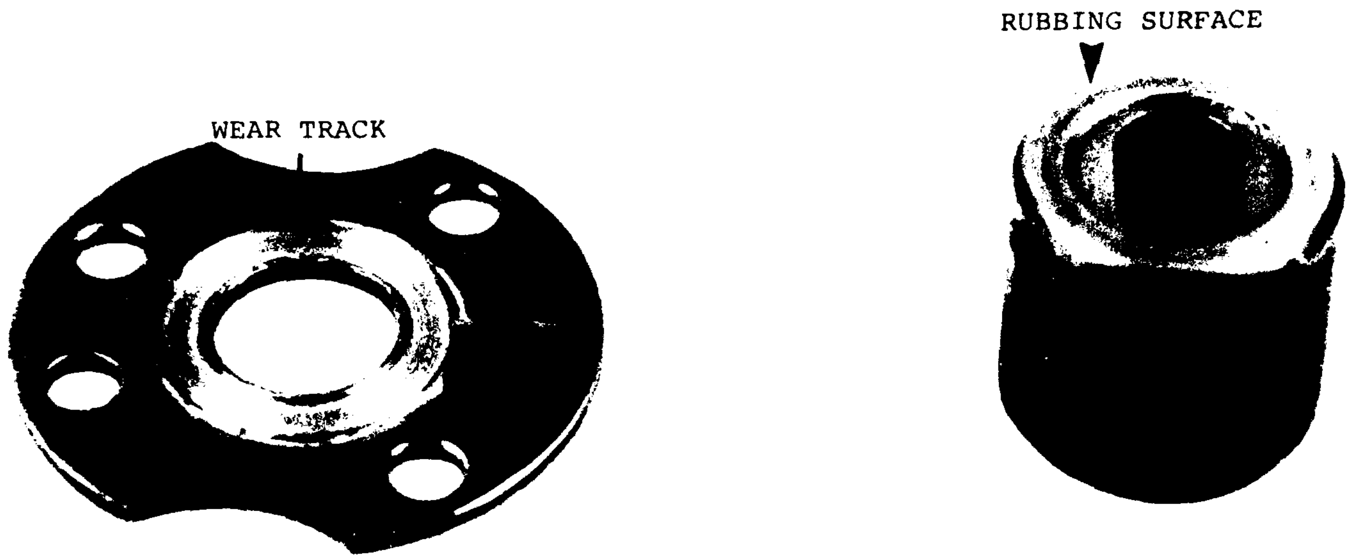

FIGURE 5. TYPICAL POSTTEST WEAR TRACK AND MATING WEAR SURFACE ON WEAR-GENERATOR COMPONENTS

The device is driven by a variable speed motor and drive shaft which is fitted into the drive plug cavity. Conditions in this program for wear were drive plug rotation at 300 rpm at a compression load of 166.8 newtons (37.5 lb) giving a load pressure of 1.12×10^{6} Pa (162 psi).

The wear coupons for this program were mild steel conforming to Federal Specification QQ-S-698, Grade 1009, No. 4 temper, 1.6×10^{-3} m (0.0625-in.) thickness. The wear coupons were cut to the shape of the hub body, but rubbing occurred only on a circular track about 3×10^{-3} m (0.1-in.) in width defined by the end faces of the drive plug. For tests without wear the wear coupons were replaced with carbon coupons, which are normally installed in a new pump; the assembled generator was placed in the test-oil sump, but did not rotate during the test.

Figure 6 is a photograph illustrating the assembled components of the test-oil sump just prior to installation in the sump container. As shown, most of the components are attached to the sump lid which is then attached to the top of the sump and consequently appears schematically as shown in Figure 3. Shown in Figure 6 is the test-oil pump, wear generator with attached wear-coupon load springs, float, thermocouples (2 ea), test-oil pump strainer, drive shafts (2 ea), and the associated plumbing. The drive motors and gearboxes (not shown) for both the test-oil pump and wear generator are installed on the topside of the cover after it is attached to the test-oil sump. Most of the oil-wetted components, except the pump bodies and float are fabricated of stainless steel. The deposit surface (test specimen) shown in Figure 2 and shown schematically in Figure 3 is made of AMS 6415 (SAE 4340) steel as was determined by the AFWAL.

Operating Procedure

Hot-wall deposition tests are accomplished by first diligently cleaning all of the oil-wetted surfaces. The deposit surface (test specimen) is cleaned to a metallic luster by scrubbing with appropriate cleaning materials. Then the rig is assembled and the heat-medium tank charged with 5P4E polyphenyl ether. The test-oil sump and auxiliary oil reservoir are charged with 2,300 and 1,000 ml of test lubricant, respectively. The test-oil pump

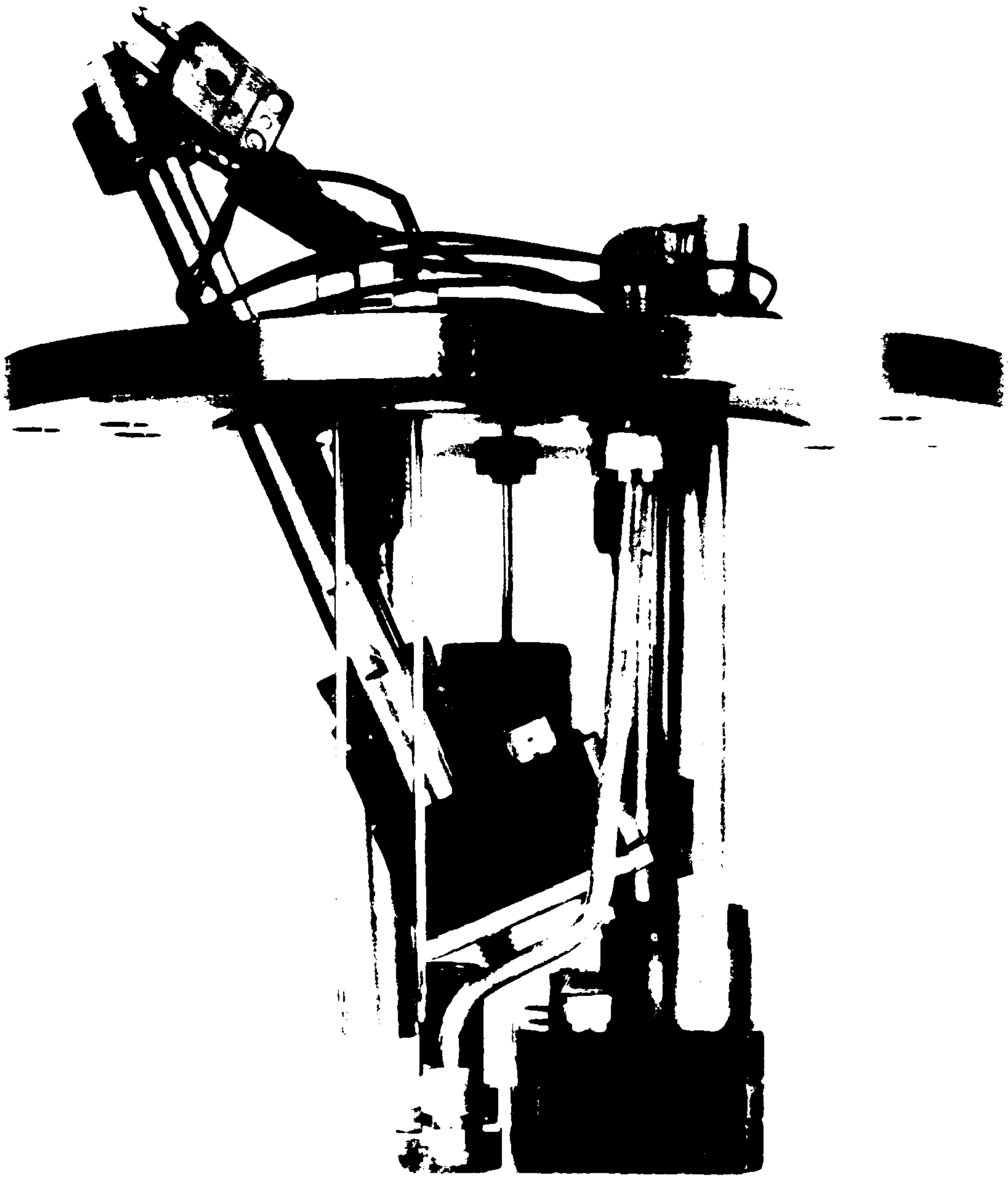

FIGURE 6. ASSEMBLED COMPONENTS OF TEST-OIL SUMP

is turned on and the air supply to the specimen housing is set at 1.65 x 10^{-4} m^3/sec (0.35 cfm). The test-oil pump is normally set at a gage pressure of 2.8 x 10^5 Pa (40 psig) initially and is later adjusted to the required pressure to provide 300-ml/min oil flow to the spray chamber. The test-oil sump and heat-medium tank heaters are then turned on to increase the sump temperature to 177°C (350°F). The temperature of the heat medium rises considerably faster and is brought up to 293°C (560°F) in steps as the sump temperature is reaching 177°C (350°F). The required temperatures are normally obtained in 30 to 45 minutes. After the test-oil flow rate is set, the solenoid valve of the automatic oil makeup system is adjusted to maintain the proper level of lubricant in the test-oil sump. For tests having wear, the wear generator is started and set at 300 rpm when the proper temperatures are obtained. Start of the test is when these temperatures are within 6°C (10°F) of the sought temperatures and are being controlled by the thermocouple-instrumented controllers. For filtration tests the appropriate filter (3 μm or 15 μm) is installed in the filter housing prior to starting heat-up. When changing filters during test, the test-oil pump is stopped and the preweighed-new filter installed in the filter housing. This requires approximately five minutes.

The normal test duration is 48 hr of continuous operation, during which the test-oil sump temperature and the heat-medium tank temperature are controlled automatically. The test-oil-in temperature is measured just ahead of the spray nozzle, but is not controlled. Generally, this temperature is less than 6°C (10°F) lower than the sump temperature A 104-watt heating tape is normally employed on the test-oil line between the sump and spray nozzle to maintain this temperature within the 6°C (10°F) temperature spread. For filtration tests it was found that the heating tape was necessary to prevent exceeding the allowed temperature drop. All exterior oil-in lines are wrapped with insulation after installing the heating tape. Also, the outside of the heat-medium tank is wrapped with insulation to aid in the prevention of heat losses.

Lubricant samples are drawn from the spray-chamber drain (40 ml for nonfiltration and filtration without wear and 20 ml for filtration with wear)

for 40°C (104°F) kinematic viscosity and neutralization number determinations. These are taken at 16-hr, 24-hr, 40-hr and 48-hr (end of test) test times. For filtration with wear tests, samples are also taken upstream (before filter) and downstream (after filter) from the filter at the same times. These samples are 10-ml each and are employed for trace iron (Fe) determinations by energy dispersive X-ray fluorescence spectroscopy.

When used, the mild steel wear coupons are prepared as follows:

1. Rinse and wipe with swab using toluene

2. Oven dry

3. Cool for minimum of 30 min. and weigh to nearest milligram.

The coupons are then assembled in the wear generator. Posttest treatment of wear coupons was as follows:

1. Rinse with heptane

2. Electrolytic clean

3. Dip or rinse in ionized water, isopropyl alcohol, and toluene in that order

4. Oven dry

5. Cool for minimum of 30 min. and weigh to nearest milligram.

Deposit Rating Procedure

The deposit rating procedure, used to describe numerically the deposits on the hot-wall specimen posttest, is similar to that used in the 48-hr bearing deposition test[3], the primary differences being that for the hot-wall only one surface of one item is inspected, and in the case of sludge over carbon, the carbon is employed for computing the rating.

A demerit rating number is selected to identify the different types and thicknesses of deposits present. Demerit values range from 0-20, defined as follows:

Deposit Type	Demerit Rating Number Light	Medium	Heavy
Varnish	1	3	5
Sludge	6	7	8
Smooth carbon	9	10	11
Crinkled carbon	12	13	14
Blistered carbon	15	16	17
Flaked carbon	18	19	20

This demerit number is multiplied by a number from 0 to 10, corresponding to the percent of the area, 0 to 100 percent, covered by that deposit type. In the event that more than one type of deposit is present on the rated area, the deposit rating is then the total of the individual rating values necessary to account for 100 percent of the rated area. In any event, double ratings, such as sludge over varnish, are not used. The deposit rated is that which is visible without the removal of another deposit, except in the case of sludge over carbon. In such instances, the more severe deposit type is used in the rating calculation.

Trace-Metal Analysis Procedure

Trace-metal analyses of lubricant samples were performed on an Edax Model 707B energy dispersive X-ray analyzer to yield quantitative results. Lubricant samples were mixed well and analyzed versus standards prepared using Conostan metallo-organic compounds. The precision by this method is 2 percent and a minimum of approximately 10 ppm iron (Fe) can be determined by the technique.

Test Lubricants

Specific details concerning lubricant formulation are rarely available due to the proprietary interests involved. Table 1 presents a listing of the ten lubricants included in this program with initial viscosity and neutralization number data and available information on specification type.

TABLE 1. DESCRIPTION OF TEST LUBRICANTS

Lubricant Code	Viscosity, cSt, 40°C (104°F)	Neutralization Number, mg KOH/g	Description
0-72-13	13.7	0.19	MIL-L-7808H
0-76-9	12.3	0.34	MIL-L-7808G
0-77-4	13.3	0.30	MIL-L-7808G
0-78-9	13.0	0.11	MIL-L-7808H
0-79-16	12.4	0.20	MIL-L-7808H
0-79-17	13.4	0.05	MIL-L-7808H
0-79-20	14.0	0.13	MIL-L-7808H
0-82-2	12.8	0.05	MIL-L-7808G
0-82-3	14.2	0.02	MIL-L-7808 Type
0-82-14	13.5	0.12	MIL-L-7808 Type

SECTION IV

TEST DATA SUMMARY

General

Ten lubricants were evaluated in this program, using two hot-wall deposition test rigs. The lubricants were evaluated under six different test conditions, namely, nonfiltration without wear, nonfiltration with wear, 15 μm filtration without wear, 15 μm filtration with wear, 3 μm filtration without wear and 3 μm filtration with wear. Two or more tests for all conditions were performed except for 15 μm and 3 μm filtration, both with wear, for three of the test lubricants. Duplicates of these six tests were not performed because of the confidence in the single-test data and also because sufficient test time was not available. The complete tables of test summary data for all ten of the lubricants are presented in the Appendix of this report.

In this section of the report and also in the Appendix, tables and plotted graphs of data pertaining to the ten lubricants are presented. The data will be shown in the order of the lubricant code numbers as assigned at AFWAL, and do not indicate a preference or preferential treatment of any one lubricant over another. In several of the following presentations the data are shown on more than one consecutive page and merely indicate that the information could not be presented clearly on one page only.

Hot-Wall Test Results

Averaged hot-wall test results, derived from the tables of data shown in the Appendix, are presented in Table 2. Data for the six different testing conditions (test parameters) for all ten of the lubricants are given. The test parameters for each lubricant are tabulated in the order that tended to give the maximum deposit rating first and then conditions that would give deposit ratings in descending order to a minimum. This tabulated order is as follows:

TABLE 2. AVERAGED HOT-WALL TEST RESULTS

Test Parameters		Averaged Test Results		
Avg Total Wear, g	Filter (Changes)	Deposit Rating	40°C Vis Incr,%	NN Change, mg KOH/g
		Lubricant 0-72-13		
1.11	None	90	12.0	0.87
1.53	15 μm (2)	49	10.5	0.72
1.47	3 μm (5)	48	10.6	0.54
None	None	46	10.4	0.58
None	15 μm (0)	31	7.7	0.60
None	3 μm (0)	26	9.4	0.62
		Lubricant 0-76-9		
0.71	None	53	4.0	7.08
0.65	15 μm (1)	38	5.4	6.42
1.08	3 μm (4)	19	3.4	5.05
None	None	14	0.9	1.98
None	15 μm (0)	20	0	1.52
None	3 μm (0)	22	-0.1	1.49
		Lubricant 0-77-4		
1.65	None	56	2.7	0.91
1.58	15 μm (3)	53	1.2	0.75
1.60	3 μm (8)	47	2.7	0.53
None	None	30	3.7	0.94
None	15 μm (0)	23	1.6	0.72
None	3 μm (0)	22	-1.0	0.40
		Lubricant 0-78-9		
1.29	None	90	10.4	0.46
1.54*	15 μm (2)	63	10.0	0.34
2.06*	3 μm (5)	67	11.1	0.30
None	None	41	8.3	0.24
None	15 μm (0)	43	9.1	0.22
None	3 μm (0)	39	7.8	0.14
		Lubricant 0-79-16		
1.40	None	57	9.3	0.49
1.74	15 μm (3)	77	9.5	0.20
1.71	3 μm (5)	49	9.0	0.23
None	None	27	8.3	0.26
None	15 μm (0)	27	6.7	0.12
None	3 μm (0)	23	7.5	0.14

* Single test.

TABLE 2. AVERAGED HOT-WALL TEST RESULTS (Cont'd)

Test Parameters		Averaged Test Results		
Avg Total Wear, g	Filter (Changes)	Deposit Rating	40°C Vis Incr,%	NN Change, mg KOH/g
		Lubricant O-79-17		
1.99	None	100	16.9	0.64
2.04	15 μm (3)	90	17.2	0.61
1.95	3 μm (7)	86	18.0	0.57
None	None	41	14.8	0.47
None	15 μm (0)	33	14.7	0.49
None	3 μm (0)	24	15.1	0.49
		Lubricant O-79-20		
1.87	None	111	8.8	0.68
1.80	15 μm (3)	84	8.5	0.38
1.72	3 μm (7)	49	8.6	0.42
None	None	33	7.1	0.29
None	15 μm (0)	32	6.8	0.37
None	3 μm (0)	26	6.4	0.27
		Lubricant O-82-2		
1.62	None	67	8.1	1.46
1.86*	15 μm (3)	47	8.4	1.29
1.41*	3 μm (5)	46	7.4	1.10
None	None	22	7.0	1.37
None	15 μm (0)	23	7.2	1.17
None	3 μm (0)	21	7.3	1.40
		Lubricant O-82-3		
1.72	None	66	23.1	2.06
1.04*	15 μm (1)	14	15.1	0.67
1.36*	3 μm (2)	14	17.0	0.90
None	None	16	12.1	0.47
None	15 μm (0)	10	10.9	0.46
None	3 μm (0)	11	11.3	0.54
		Lubricant O-82-14		
1.97	None	88	12.5	1.54
1.51	15 μm (4)	54	12.2	1.27
1.70	3 μm (9)	81	12.0	1.12
None	None	37	9.6	0.80
None	15 μm (0)	33	11.4	0.91
None	3 μm (0)	39	10.1	0.89

*Single test.

Test Parameters

- Wear — No filtration (screen)
- Wear — 15 μm filtration
- Wear — 3 μm filtration
- No wear — No filtration (screen)
- No wear — 15 μm filtration
- No wear — 3 μm filtration

Early in the program it was hypothesized that this would be the order of decreasing deposition and as seen by studying Table 2 is fairly accurate. While it would have been desirable to control coupon wear for each wear test as a fixed parameter instead of an "uncontrolled variable", as actually resulted, it was necessary to normalize or adjust the wear in the statistical analysis (presented later in this section of the report). This approach was used so that the response variable, as deposit rating would be, was a best estimate of what it would have been if total wear were always the same. Because the three response variables, deposit rating, viscosity increase, and neutralization number (NN) change are discussed in detail in the statistical analysis subsection they will not be expounded upon here. On the other hand, other observations of interest will be discussed.

<u>Filter Changes</u>. Early in the program when considering the appropriate filters to be utilized, it was recommended by personnel at APM that the filter area be sized for the test-oil flow rate to be used during testing. As discussed in Section II of this report, it was stated that normal flow densities for turbine engine lubricant systems are in the range of 407-1222 $\ell/min/m^2$ (10-30 gpm/ft^2), and minimum recommended is 41-204 $\ell/min/m^2$ (1-5 gpm/ft^2). It was explained to APM personnel that wear-metals would be generated, therefore, the recommended filters (15 μm and 3 μm) and filter housing as shown in Figure 7 were supplied. It can be seen that the size of the filters is relatively small. On the other hand, the test system, even though employed for accelerated testing, is small and contains only 3,300 ml (2,300-ml in test-oil sump and 1,000-ml in auxiliary reservoir) of test lubricant total. In Table 2 it can be seen that all of the tests with wear-metal generation and filtration required, on the average, more than one

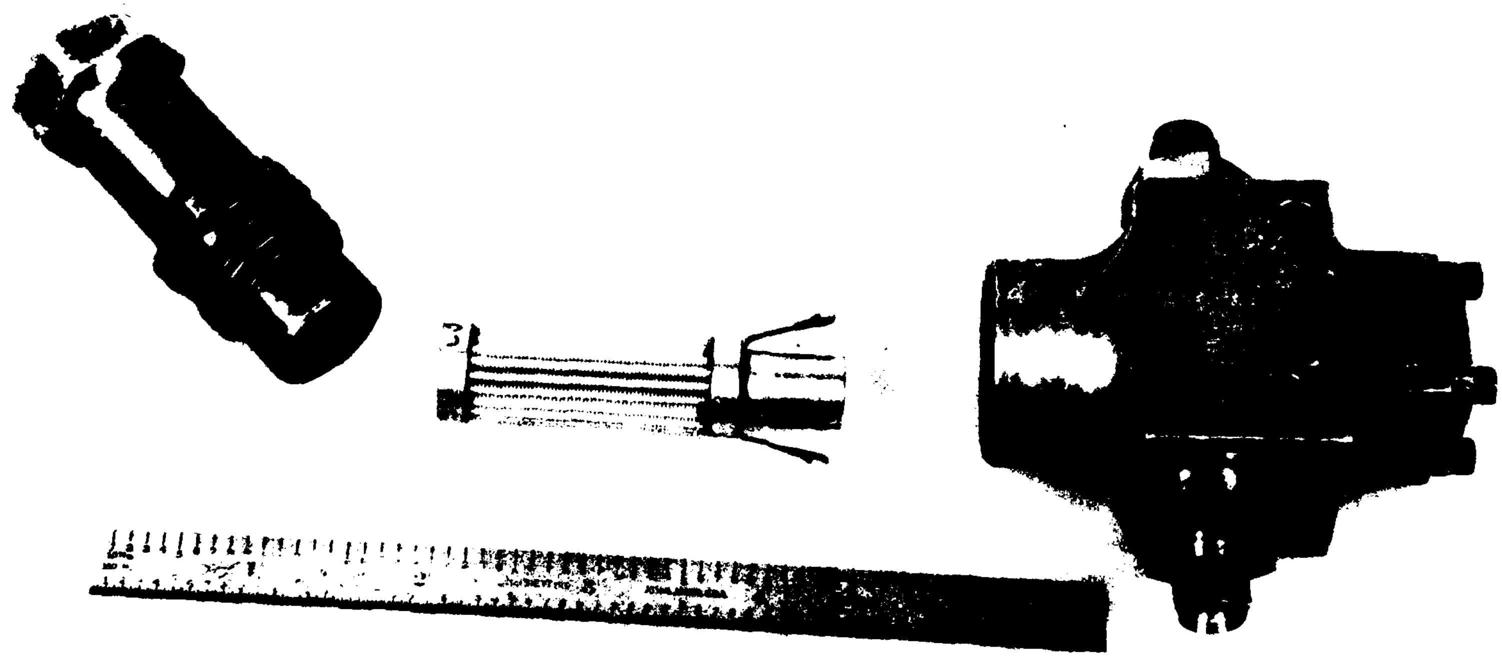

FIGURE 7. TYPICAL FILTER AND FILTER HOUSING

filter per test. In fact for 3 μm filtration, lubricants O-77-4 and O-82-14 required nine and ten filters, respectively. NOTE: the total number of filters used during a test is actually one more than shown in the table in parenthesis, which is tabulated as number of filter changes. Nine or ten filters used during a test means the filters were being changed approximately every five hours. Also note in Table 2 that significantly less 15 μm filters than 3 μm filters were required for wear tests, and for filtration tests without wear, only one filter was required for each individual test (15 and 3 μm) with all ten lubricants. Having to change the filters so often in the wear generation tests indicates that the filters may have been undersized, especially where up to 2 g of wear particles are generated into an oil system of this size.

Shown in Table 2 is the fact that lubricant O-82-3 required less filter changes (both 15 and 3 μm filter tests) than any of the other nine lubricants. One other lubricant, O-76-9, stands out as using less filters than normally experienced, but this lubricant also displayed less wear than O-82-3 which indicates more strongly that the latter stands out as exhibiting less filter plugging. Briefly observing other data shown in the table for O-82-3 shows that it is very sensitive to filtration and the filter tests, both wear and nonwear, gave the lowest deposit ratings of any of the lubricants. Even though this lubricant without filtration, both with and without wear, gave deposit ratings lower than average ratings as compared to other lubricants, the effect of filtration was significantly positive. Wear-test data for this lubricant also indicate that both viscosity increase and neutralization number increase, and possibly wear, are lessened significantly by filtration. It also appears that 15 μm filtration is probably as good as if not superior to 3 μm filtration for all filtration conditions for lubricant O-82-3.

Coupon Wear. Table 3 presents average wear as determined by weighing the coupons both pretest and posttest. The average coupons wear that would be expected for each lubricant regardless of whether the test was with or without filtration is shown in the column tabulated average wear. The standard error expected for this average wear value is shown in the last column. Below the average wear data for all of the ten lubricants is a

TABLE 3. LUBRICANT/COUPON WEAR COMPARISON

Lubricant Code	Average Total Coupon Wear, g			Avg Wear, g[a]	Std Error, g[b]
	No Filter	15 μm	3 μm		
0-72-13	1.11	1.53	1.47	1.37	0.13
0-76-9	0.71	0.65	1.08	0.81	0.13
0-77-4	1.65	1.58	1.60	1.61	0.02
0-78-9	1.29	1.54[c]	2.06[c]	1.63	0.23
0-79-16	1.40	1.74	1.71	1.62	0.11
0-79-17	1.99	2.04	1.95	1.99	0.03
0-79-20	1.87	1.80	1.72	1.80	0.05
0-82-2	1.62	1.86[c]	1.41[c]	1.63	0.13
0-82-3	1.72	1.04[c]	1.36[c]	1.37	0.20
0-82-14	1.97	1.51	1.70	1.73	0.13
		Pooled Avg Wear		1.56	
		Std Error		0.10[d]	

(a) Average coupon wear for all wear tests with each particular lubricant consisting of tests with no filtration, 15 μm and 3 μm filtration.

(b) Standard error for average wear described in (a).

(c) Single test only for this condition.

(d) Pooled average wear and standard error for the ten lubricant wear averages described in (a).

pooled average wear with expected standard error. A total of 68 wear tests were employed to derive these pooled values. It is interesting to note that lubricant O-79-17 stands out as having significantly highest wear and O-76-9 significantly lowest wear.

During early testing in this program (lubricants O-72-13, O-76-9, and O-79-16) only lubricant O-76-9 required higher wear-generator drive torque as was evidenced by stalling of the wear-generator drive motor on numerous wear tests, while at the same time less wear was associated with this lubricant. No instances of wear-generator motor stalling resulted when testing lubricants O-72-13 or O-79-16. Subsequent to testing these three initially employed lubricants and having the associated motor-stalling problems, a 5 to 1 gear ratio gearbox was installed in each wear-generator drive system. After that no problems were encountered with motor stalling, but on the other hand it is not known if the required torque to drive the wear generator for the seven remaining lubricants equaled or exceeded that required for O-76-9. Since the scope of this program was not to determine friction torque data for the various lubricants, the test rigs were not so instrumented. It appears that such friction information would be desirable and should definitely be considered for future investigations. Regardless, the friction and wear characteristics for O-76-9 appear to be significantly different than at least some of the lubricants utilized in this study.

Statistical Analysis

The data to be analyzed in this study consisted of three response variables, namely:

- Deposit rating
- Viscosity increase at 40°C, %
- NN change, mg KOH/g

The test parameters included total wear (in grams), filter type (none, 3 or 15 μm) and lubricant type (ten varieties). The purpose of the analysis was to determine if the test parameters had any effect on each of the response variables.

The statistical methodology chosen in achieving this objective was analysis of covariance. In this technique the averages of the three response variables (deposit rating, viscosity increase and NN change), at each of the 30 combinations of three filter conditions and ten lubricant types, are adjusted for the effects of total wear. The adjusted means then are compared among themselves to determine if any are statistically different. Such an adjustment was made so that the response variable means are the best estimates of what they would have been if the total wear had been the same for all filter and lubricant combinations.

The adjustment for total wear was made by first fitting a straight line of each of the three response variables against the values of total wear. For example, a straight-line fit would be made of the deposit rating as a function of total wear using linear regression techniques. These line fits were made for each of the combinations of filter conditions and lubricant types. The response variable means for the different wear values associated with them were then adjusted to what they would have been had they a common average total wear.

This is illustrated for an idealized case in Figure 8 where the deposit rating averages for two filter-lubricant combinations are fitted to straight-lines as a function of the total wear. For each filter-lubricant group, variation in total wear contributes to the variation in deposit rating. Hence, the distance between the two wear values, $\bar{W}_1$ and $\bar{W}_2$, affects the difference between the two corresponding deposit ratings, $\bar{D}_1$ and $\bar{D}_2$. If the deposit ratings had been observed from some common wear value, say W_0, then they would be comparable. Thus, the need for adjusting the deposit rating means is apparent. This is shown on the graph in the large discrepancy between the observed and adjusted deposit rating means.

Table 4 consists of a summary of the results of the analysis of covariance using deposit rating as the response variable. The sources of variation consist of lubricant differences (L), filter differences (F), lubricant-filter interactions (LxF), wear differences (W) and the experimental error. The fourth column, labelled F, contains the value of the F test statistic for determining whether or not a given source of variation is influential. The last column, labelled p, gives the significance of the corresponding

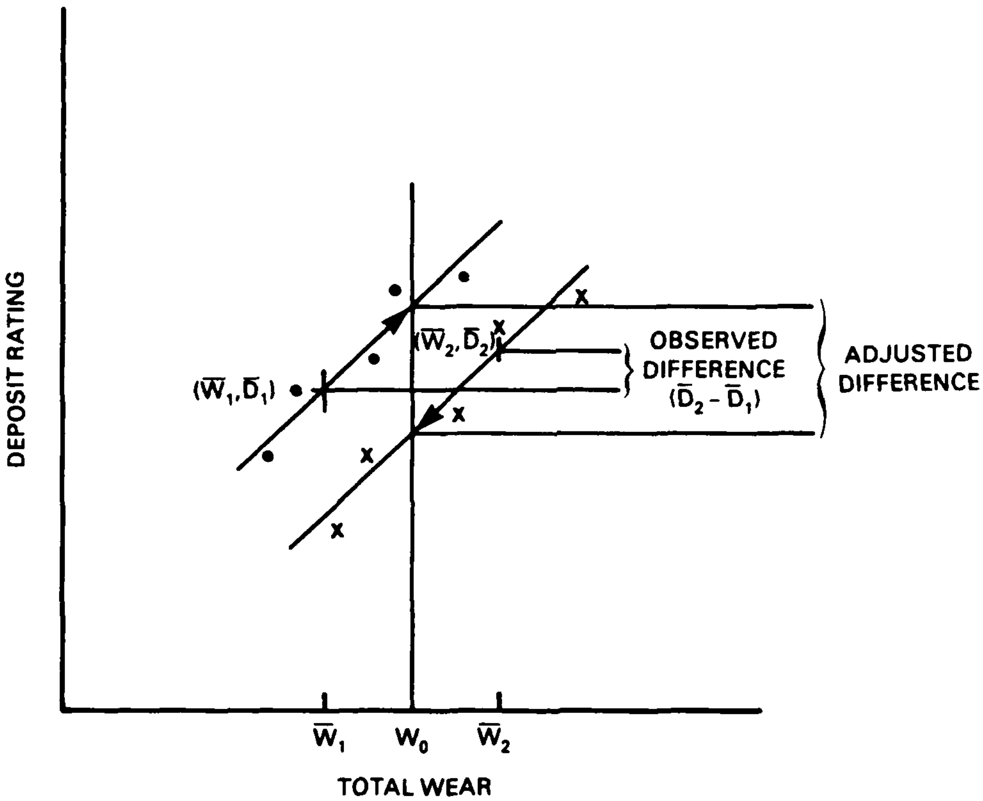

FIGURE 8. IDEALIZED EXAMPLE OF ADJUSTMENT OF DEPOSIT RATING MEANS

test statistic. A low p value, say $<.05$, indicates that there is a very small error (e.g., <5 percent) in concluding that the deposit rating means, across the combinations of the given source of variability, are statistically different. A large p value, say $>.05$, indicates that the deposit rating means are not statistically different for the given source of variation.

Analyzing Table 4, it can be seen that all sources of variability are significant. Total wear, lubricant types, and filter condition all have a significant influence ($p<.0001$) on the mean deposit ratings. Also, there is a significant interaction among lubricants and filters.

These results imply that differences in total wear are important when comparing lubricants and filters with respect to deposit ratings. And, when these wear adjustments are considered, there exist combinations of filter size and lubricant type that have deposit rating means that are significantly different from each other. This latter result is understood more easily by viewing Figure 9.

TABLE 4. ANALYSIS OF COVARIANCE TABLE FOR DEPOSIT RATING

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Lubricant (L)	9	12100.4	1344.5	11.87	.0000
Filter (F)	2	6555.8	3277.9	28.93	.0000
LxF	18	4617.2	256.5	2.26	.0051
Wear	1	47469.8	47469.8	419.00	.0000
Error	110	12463.6	113.3		
Total	140				

Figure 9 indicates that the lowest deposit rating average occurs with lubricant 0-82-3 and filter size 3 or 15 μm. The highest occurs when there is no filter and the lubricant is 0-"2-13, 0-78-9, 0-79-17, or 0-79-20. There is clearly a significant difference ($p<.01$) between the deposit rating averages when no filter is present versus those when a filter is available. Also, while the average ratings with the 15 μm filter are slightly higher than those for the 3 μm filter, and certain lubricants appeared to respond

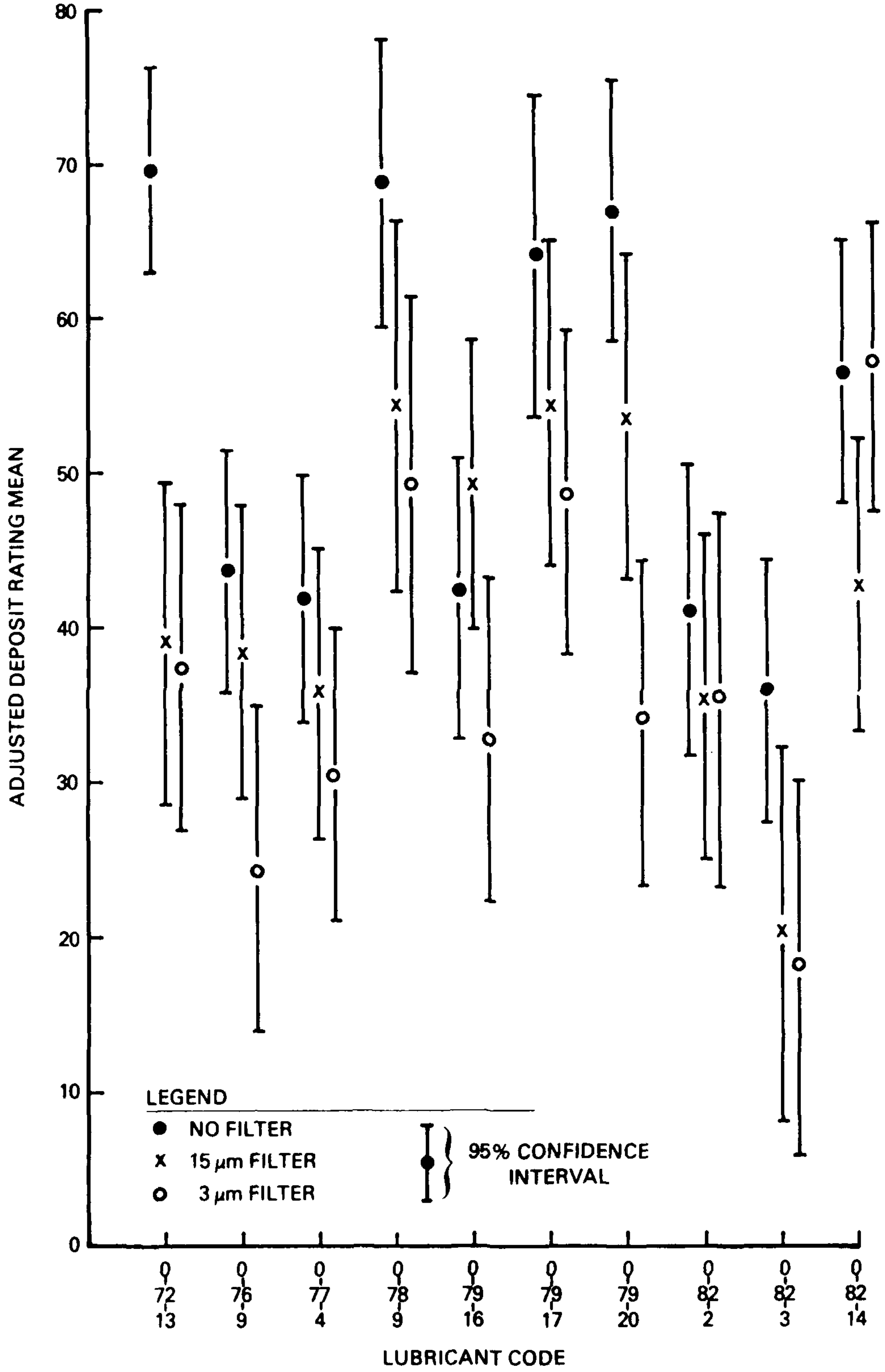

FIGURE 9. DEPOSIT RATING MEANS ADJUSTED FOR WEAR VERSUS LUBRICANT AND FILTRATION

differently, there is no statistically significant difference between the overall deposit means for these two groups using the analysis technique selected. Looking separately at the lubricants, lubricants 0-82-3, 0-82-2, 0-76-9, and 0-77-4 are significantly lower than the others in average deposit ratings, while lubricants 0-72-13, 0-78-9, 0-79-17, and 0-79-20 are significantly higher. Other conclusions of this type can be drawn by carefully observing Figure 9.

Each adjusted deposit rating mean in Figure 9 has associated with it a 95 percent confidence interval. These are illustrated by means of enclosed vertical lines. The center of the line (plotted data point) is the adjusted mean while the end bars indicate the 95 percent confidence interval.

When considering the remaining two response variables, viscosity increase and NN change, the covariate based on total wear was not significant ($p>.05$). This implies that total wear has no effect on these variables and that the lines in Figure 8 essentially have slopes of zero (i.e., the observed and adjusted differences are the same). Hence, the remaining analyses are based on analysis of variance rather than analysis of covariance techniques. In this approach the means of viscosity increase and NN change are compared, for each combination of filter condition and lubricant type, without adjusting for the total wear values. Tables similar to Table 4 are derived but they do not contain a source of variability due to wear.

Table 5 contains the analysis of variance results using viscosity increase and NN change. From the F statistics in column 5 and the p values in column 6, it can be seen that no significant interaction exists between lubricant and filter. Also, no significant differences exist among the viscosity increase and NN change means for the three filter conditions. The only observable differences were among the ten lubricant averages for both viscosity increase and NN change. However, visually examining the averaged neutralization number data shown in Table 2 for the various testing conditions does show what appears to be a filtration effect. For all ten lubricants tested with wear it can be seen that filtration decreased the NN change regardless of whether the average total wear was more or less. Also eight of the ten lubricants exhibited improved NN change for 3 μm filtration over 15 μm filtration where wear was present. The nonwear tests did not consistently show this relationship and it appears that there was no significant interaction between lubricant and filtration for this test condition.

A rank ordering of the means for viscosity increase and NN change for the ten lubricants is given in Table 6. For viscosity, lubricants O-79-17 and O-82-3 have significantly higher averages than the other lubricants, while lubricants O-76-9 and O-77-4 have significantly lower means. For NN change, lubricant O-76-9 has a significantly higher average than all others while lubricants O-79-16 and O-78-9 have significantly lower means.

In addition to these presentations of data (Figure 9 and Table 6), Figures 10, 11 and 12 illustrate bar graphs for averaged deposit rating, viscosity increase and NN change for all ten lubricants. These are arranged in the order of the lubricant code numbers and each response variable requires two pages for presentation. Not only can the various lubricants be compared from these graphs, but they are especially useful for comparing the effects of no wear vs wear for each filtration condition for each lubricant. Also the effects of filtration for each lubricant are again very clearly illustrated. Comments and discussions that have already been advanced would again be applicable.

Lubricant Wear-Metal Analyses

Energy Dispersive X-ray Fluorescence (XRF). Lubricant samples that were collected during all wear tests (with and without filtration) were analyzed for trace amounts of iron (Fe) by X-ray fluorescence. Plots of these data, for the ten lubricants, are presented in Figure 13. Again this figure is shown on two consecutive pages of the report because of space and clarification purposes. As expected and shown by Figure 13, the wear tests without filtration tended to have significantly higher average iron content values throughout the test than those having filtration. It is surprising that lubricant O-82-2, employing wear-without filtration, had significantly higher iron content than any of the other fluids, especially since average total coupon wear as shown in Table 3 was close to the overall average. It is also interesting that O-79-16 with filtration, generally and consistently (both levels of filtration and both before filter and after filter results) had lower values than most of the other lubricants with slightly above overall average coupon wear. Also, lubricant O-76-9 displayed above average iron content in filtered lubricant samples while it had significantly lower coupon wear than any of the other nine lubricants. For many of the tests

TABLE 5. ANALYSIS OF VARIANCE TABLE FOR VISCOSITY INCREASE AND NN CHANGE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F	P
		Viscosity Increase			
Lubricant (L)	9	2418.22	268.69	51.05	0.0000
Filter (F)	2	21.04	10.52	2.00	0.140
LxF	18	45.22	2.51	0.48	0.963
Error	111	584.24	5.26		
Total	140				
		NN Change			
Lubricant (L)	9	181.94	20.22	23.00	0.0000
Filter (F)	2	3.07	1.53	1.75	0.179
LxF	18	5.42	0.30	0.34	0.994
Error	111	97.57	0.88		
Total	140				

TABLE 6. MEAN COMPARISONS OF VISCOSITY INCREASE AND NN CHANGE

Lubricant Code	Average 40°C Viscosity Incr,%	Lubricant Code	Average NN Change, mg KOH/g
0-79-17	16.07*	0-76-9	4.35*
0-82-3	14.26*	0-82-2	1.42
0-82-14	11.32	0-82-14	1.10
0-72-13	10.38	0-82-3	0.80
0-78-9	9.33	0-77-4	0.74
0-79-16	8.53	0-72-13	0.66
0-79-20	7.74	0-79-17	0.54
0-82-2	7.67	0-79-20	0.41
0-76-9	2.60*	0-79-16	0.29*
0-77-4	2.10*	0-78-9	0.25*

*Indicates these means were statistically different from all the others

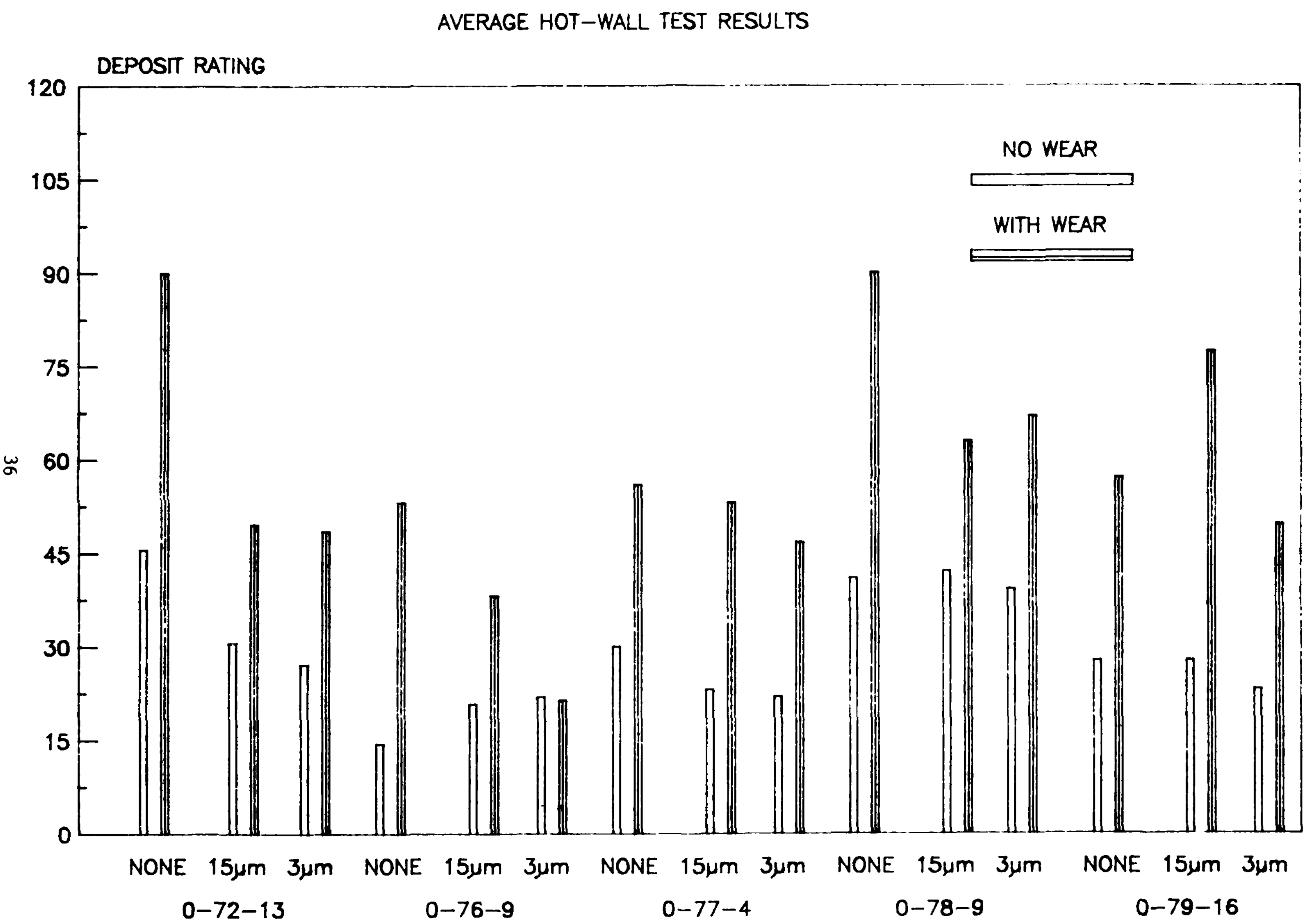

FIGURE 10. EFFECT OF FILTRATION ON DEPOSIT RATING

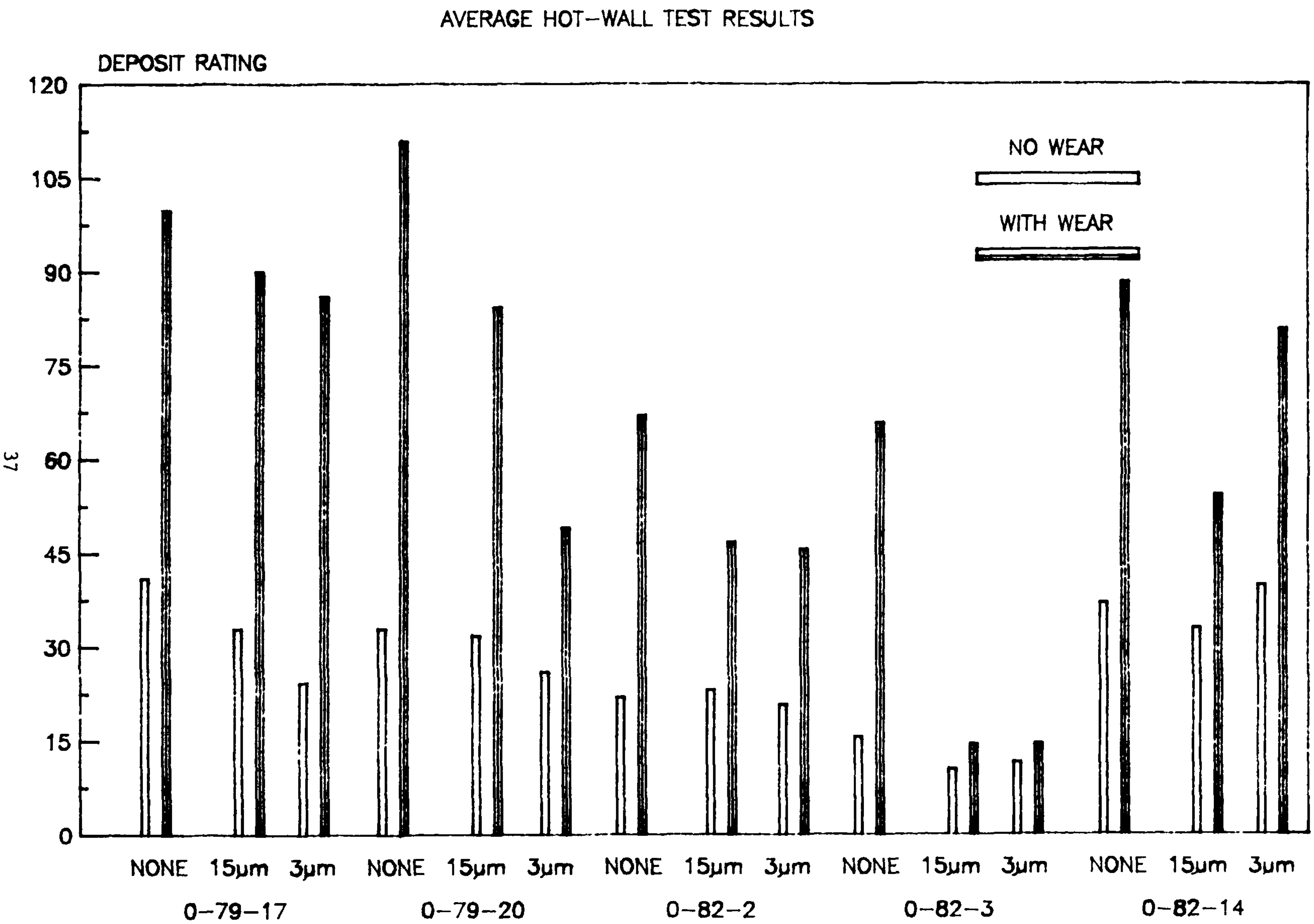

FIGURE 10. EFFECT OF FILTRATION ON DEPOSIT RATING (CONT'D)

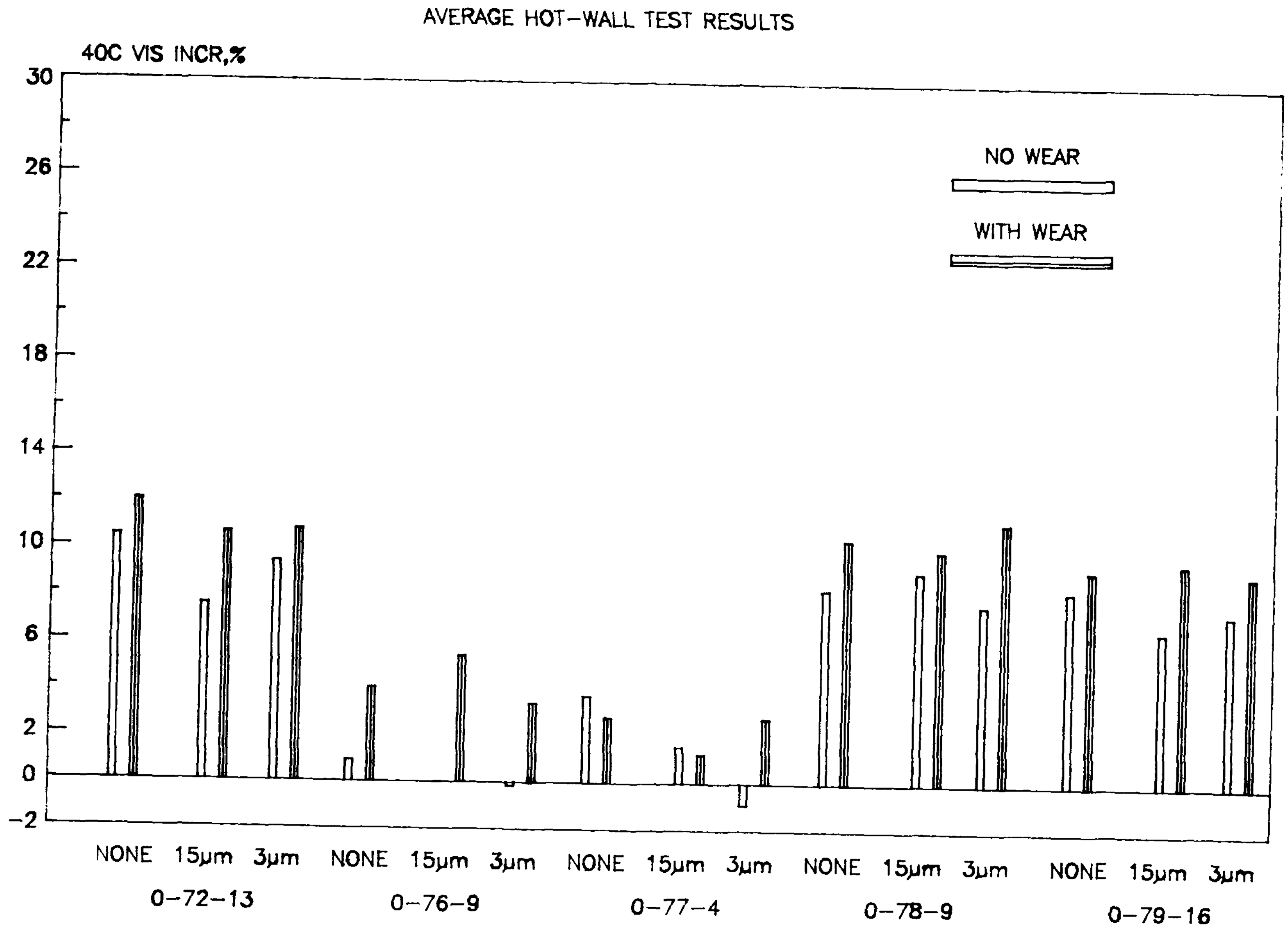

FIGURE 11. EFFECT OF FILTRATION ON VISCOSITY CHANGE

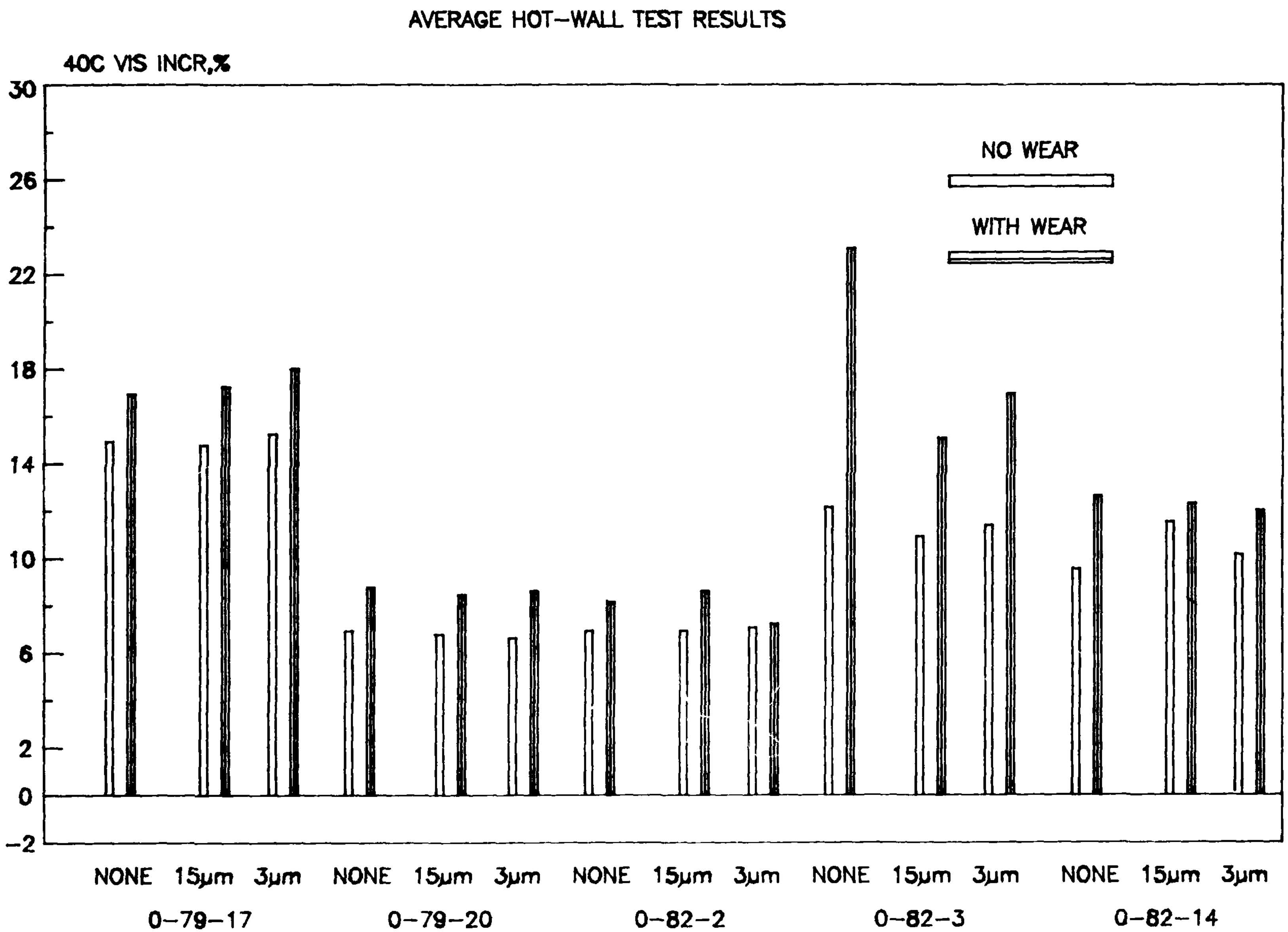

FIGURE 11. EFFECT OF FILTRATION ON VISCOSITY CHANGE (CONT'D)

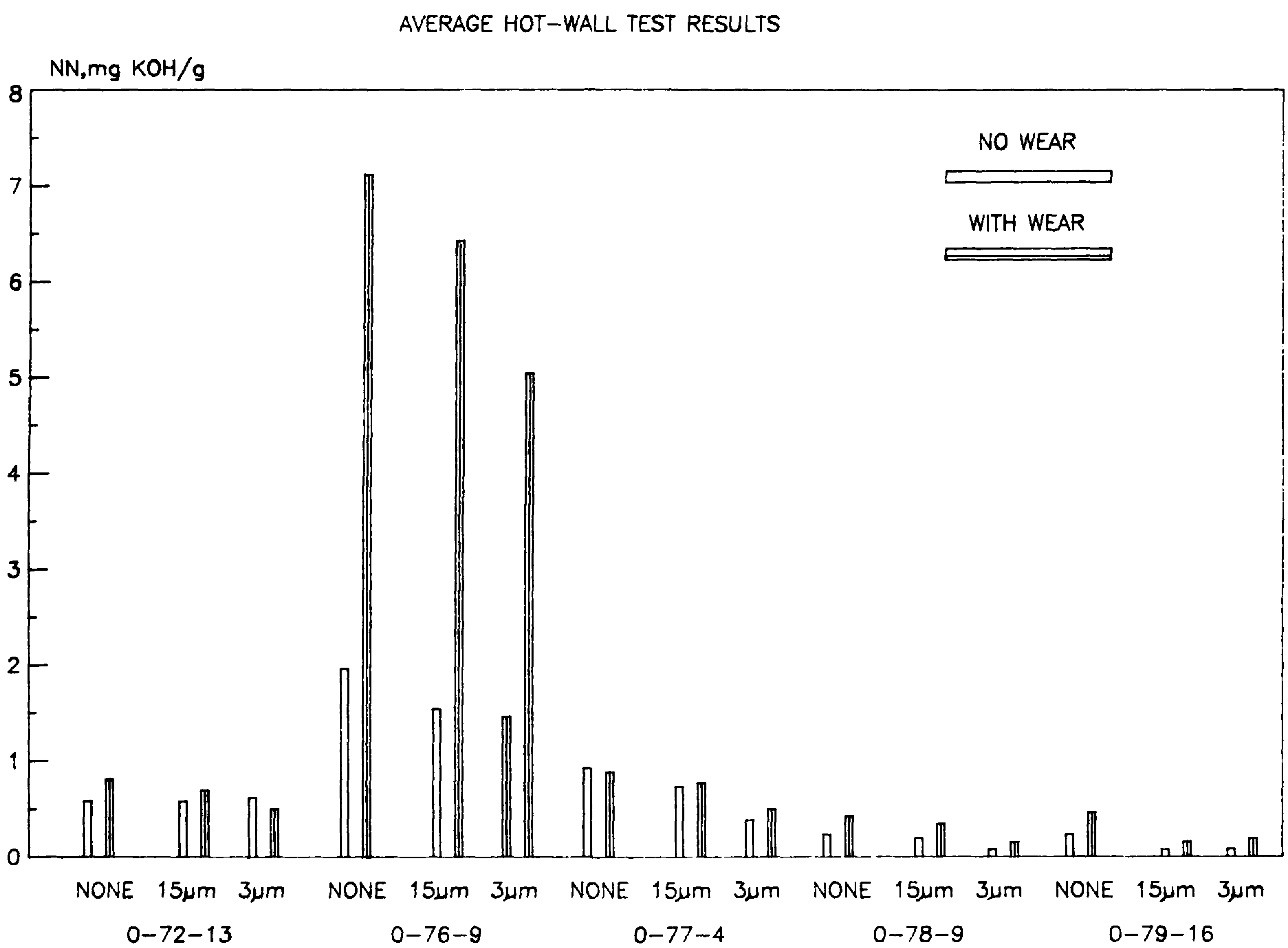

FIGURE 12. EFFECT OF FILTRATION ON NEUTRALIZATION NUMBER CHANGE

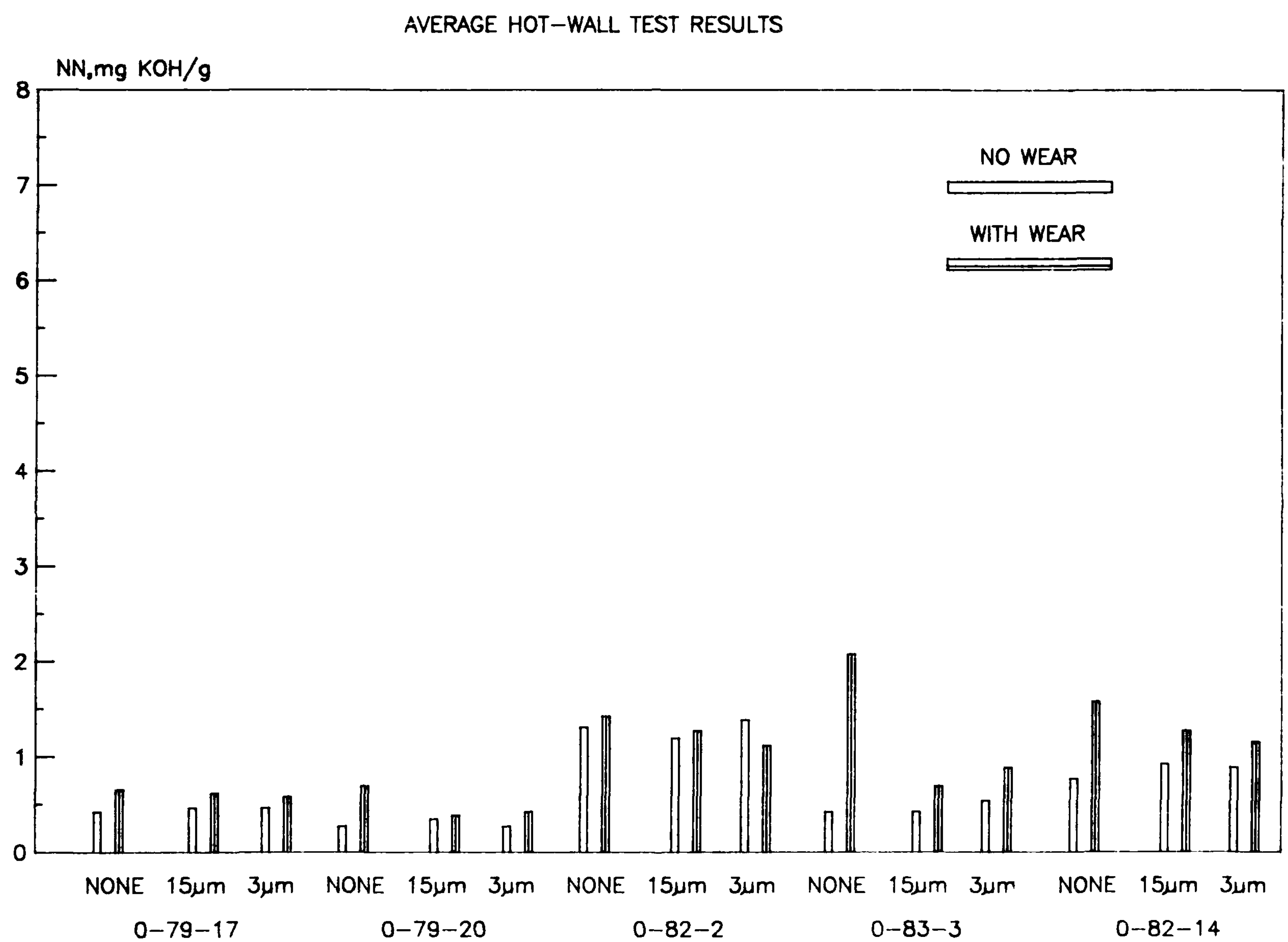

FIGURE 12. EFFECT OF FILTRATION ON NEUTRALIZATION NUMBER CHANGE (CONT'D)

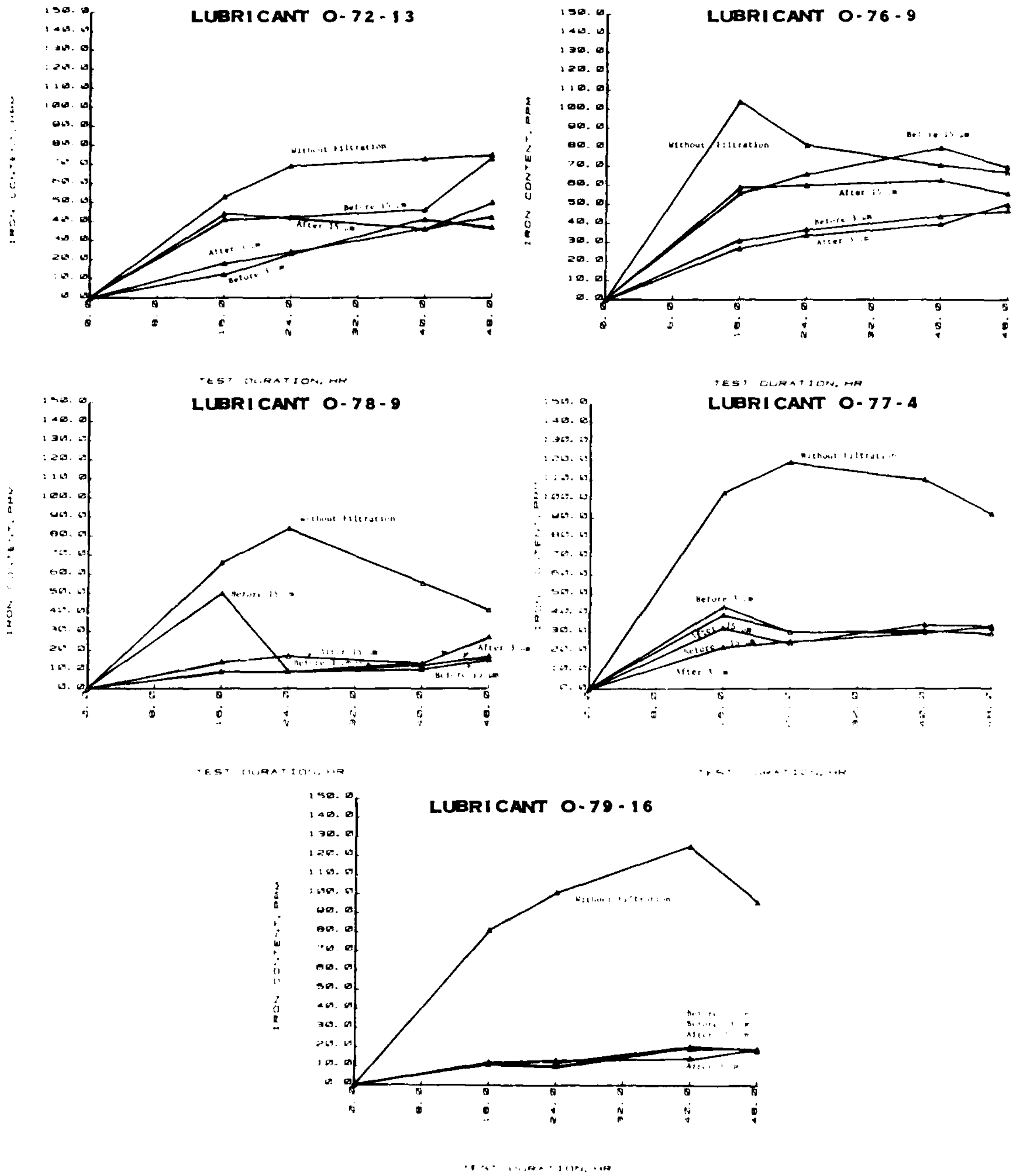

FIGURE 13. AVERAGE IRON CONTENTS DURING WEAR TESTS

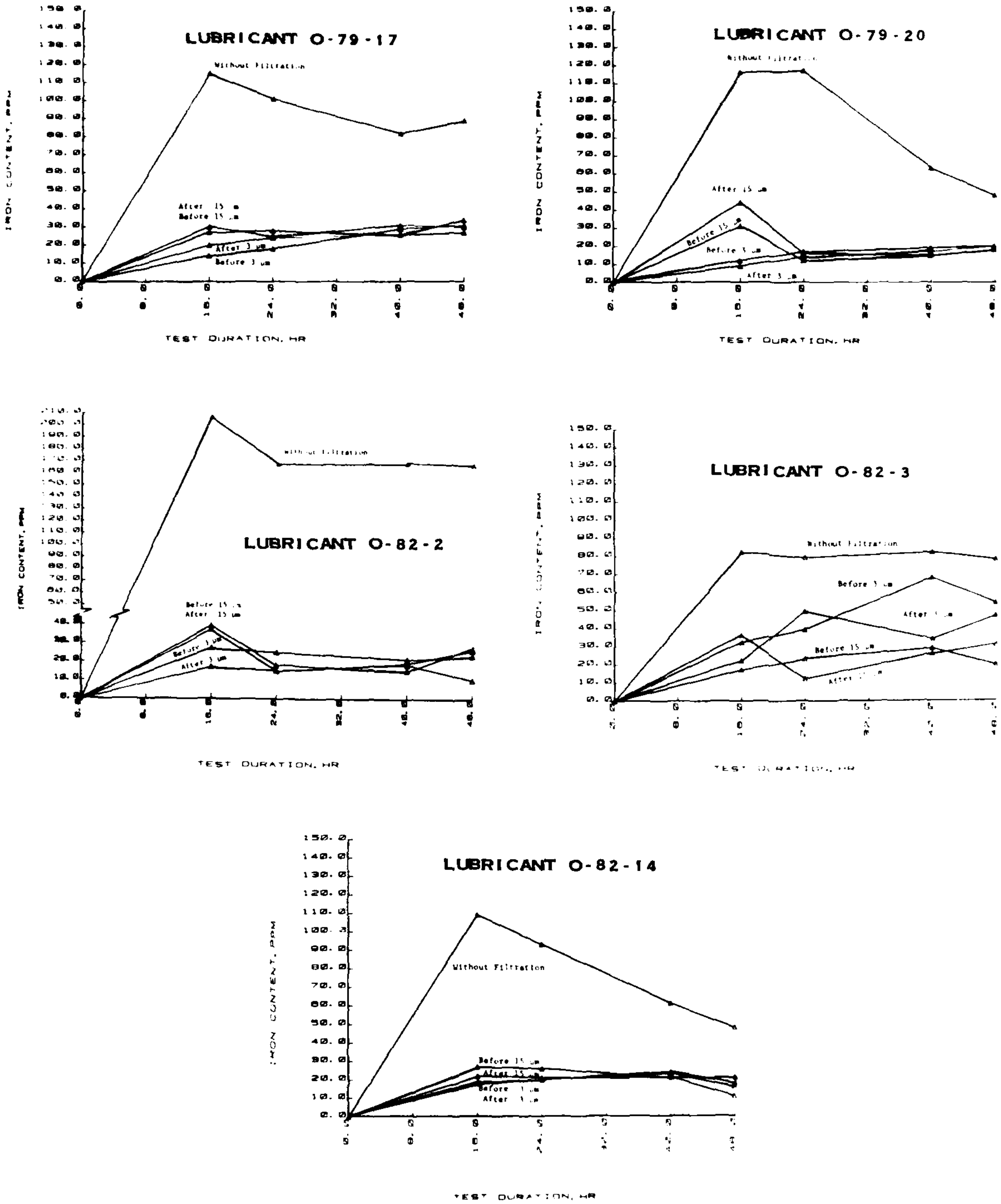

FIGURE 13. AVERAGE IRON CONTENTS DURING WEAR TESTS (CONT'D)

there did not appear to be a significant difference between the two levels of filtration, or between the before and after filter results. Generally in the tests without filtration and in several of the tests with filtration (more prevalent in 15 μm filtration) the iron content reached a high value early in the test and tended to either decline or remain fairly constant as the test continued. This happened within the first 16 hours of nonfiltration tests for four of the lubricants. Two reasons can be advanced as possibilities for this occurrence; first the coupon wear is probably greatest during the first part of the test, and secondly much of the wear debris is probably continually falling to the bottom of the lubricant sump and not being circulated throughout the system. Regardless, the fact that for most lubricants tested, there was no significant difference between the two levels of filtration (15 μm and 3 μm) or the before and after samples suggests that there are also many small particles of iron in the lubricant system that are in suspension and passing conveniently through the filters.

Ferrographic Analyses. Fairly early in the program used-oil samples from wear tests without filtration were sent to the AFWAL for ferrographic analysis. Later on, more used-oil samples from wear tests with 3 μm filtration were sent and lastly used micronic filters (both 15 μm and 3 μm) as well as new-oil and used-oil samples from wear with no filtration tests were sent to AFWAL for ferrographic analysis.

The 3 μm filters were backwashed with hexane, the hexane was evaporated and 10 ml of MIL-L-7808 oil was added to the solid material at AFWAL[4]. From this sample a ferrogram was prepared for each filter element. Microscopic examination revealed that particulates recovered from all three filters were quite similar and were classified as follows:

- Heavy normal rubbing wear
- None to a few severe wear particles
- None to a few cutting wear particles
- Moderate to heavy in chunks of debris
- Few to heavy in laminar particles
- No spheres

- Heavy in dark metallo-oxide particles--probably carbon
- Few to moderate red oxide particles
- Few corrosive wear debris particles
- Few to heavy nonferrous metal particles - some are probably aluminum, brass or copper
- None to few inorganic nonmetallic birefringent particles
- No organic nonmetallic birefringent particles
- Moderate nonmetallic, amorphous particles-carbon
- No friction polymers
- None to few fibers

Ferrograms were also prepared for a new-oil sample and used-oil samples[4] taken at 4-hr, 8-hr, 12-hr, 16-hr and 48-hr (end of test) intervals from a mild steel wear test with no filtration. Highlights of ferrographic analyses of these samples are as follows:

New oil had a few each of normal rubbing wear, severe wear, laminar, corrosive wear and nonmetallic, amorphous particles with moderately-light nonferrous metal such as aluminum and inorganic nonmetallic particles. The new oil also had moderate to heavy red oxide particles and chunks of material.

Used oil samples were very similar in many respects, but had moderate to heavy normal rubbing wear particles and heavy dark metallo-oxide particles such as carbon. There were also a few to heavy nonferrous particles such as aluminum. It is interesting to note that the chunks that were heavy in the new oil were reduced to a few to moderate in the used samples. It is also of interest that normal rubbing wear particles in the 4-hr, 8-hr, 12-hr and 16-hr samples were very heavy, but had dropped to moderate in the 48-hr (end of test) sample. This agrees somewhat with average iron content plots for nonfiltration tests that have just been discussed, where iron content decreases from 16 hr toward the end of the tests as determined by XRF.

Based on the above discussed ferrographic determinations on oil samples and also on previously AFWAL analyzed samples, it can be stated that the

generated wear particles were primarily magnetic, small rubbing wear particles in the 3-5 μm range. There were a few severe wear particles, greater than 10 μm, some blued due to temperature. The amount of wear in a test was considered to be high but type of wear was considered to be normal.

Additional Chemical Analysis of Lubricant Samples

A new-oil sample and used-oil samples discussed in the previous subsection under ferrographic determinations were subjected to further chemical analysis at AFWAL. These samples were of lubricant 0-82-3 and the used-oil samples were from Test No. 1015-3-21 (shown in Table 15 in Appendix), performed with wear, no filtration.

Based upon these determinations at AFWAL[5] the following data and brief discussions are presented:

Complete Oil Breakdown Rate Analyzer (COBRA)* Results

Oil Sample	COBRA Units
New oil	3
4-hr	4
8-hr	7
12-hr	16
16-hr	22
48-hr	182

High COBRA values are associated with oxidative and thermal stressing of lubricants. The values above suggest gradual degradation of the lubricant until 16 hr when a COBRA value was achieved that is typical of a used turbine lubricant. However, at 48 hr the lubricant had been stressed to the point that it was far beyond acceptable limits for a turbine lubricant.

Gas Chromatography. Gas chromatography of the lubricant samples indicated that no significant changes in basestock ester composition occurred during the test.

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* An electronic oil analysis instrument manufactured by NAECO, Arlington, VA.

<u>Thin Layer Chromatography</u>. Notable antioxidant depletion was detected after the 8-hr sample. The 12- and 16-hr samples contained perhaps 50 percent of the initial antioxidant additives. At 48 hr, the antioxidants were present at less than about 3-5 percent of the initial level. At these additive concentrations, the lubricant has virtually no protection against oxidation.

SECTION V

CONCLUSIONS

A detailed description of the hot-wall deposition test rig and its operation as well as the selected micronic filters are discussed. The selected test method for evaluating deposition and degradation characteristics of turbine engine lubricants both with and without filtration and also having either mild steel wear or no wear is discussed, and appropriate test data are presented.

On the basis of hot-wall deposition tests employing ten MIL-L-7808 or MIL-L-7808 type turbine engine lubricants, the following conclusions can be made:

- The test rig, modified with a wear generator and micronic-filter test capabilities, as well as the selected test method, is appropriate for evaluating deposition and degradation of turbine engine lubricants. A hot-wall temperature different than selected might reveal improvement of the test, but for this program the 293°C (560°F) heat-medium temperature appeared to be adequate.

- The selected wear generator design and mild steel wear coupons demonstrated relatively good wear repeatability and demonstrated very good results for this study. The amount of wear produced when employing the wear generator was considered to be large, but it was also shown by ferrographic technique to be primarily normal rubbing wear. Since the selected hot-wall test is an accelerated test, the large amount of wear generated over a 48-hr testing period is not considered unrealistic.

- Statistical analysis of the hot-wall deposition data showed that there was clearly a significant difference between the deposit rating averages with no filtration as opposed to filtration with either 15 μm or 3 μm filters. Filtration improved or reduced the adjusted deposit rating mean for all conditions except two. Also, while average deposit ratings with 15 μm filtration were slightly higher than with 3 μm filtration, and certain lubricants appeared to respond differently, there was no statistically significant

difference between the overall deposit means for these two groups using the analysis technique selected.

- Considering the two response variables, viscosity increase and neutralization number change, the statistical analysis showed that total wear had no effect.

- Analysis of variance results using viscosity increase and neutralization number change revealed no significant interaction existed between lubricant and filter. Also, no significant differences existed among the viscosity increase and neutralization number change means for the three filter conditions (no filter, 15 μm filter, or 3 μm filter). On the other hand, visual examination of the averaged neutralization number data showed what appeared to be a filtration effect for tests with wear. Filtration decreased the neutralization number change for all ten lubricants and eight of the ten lubricants exhibited improved (less) neutralization number change for 3 μm filtration over 15 μm filtration. These improvements were all for tests having wear, however, nonwear tests did not show this same trend.

- Trace iron content in lubricant samples by XRF showed a general improvement (less iron particles) in both 15 μm and 3 μm filtration-wear tests over nonfiltration conditions. Many of the wear tests did not show a significant difference in iron content between the two levels of filtration, nor between the upstream and downstream (before and after the filter) lubricant samples. This suggests that there were many small particles of iron in the lubricant in suspension that passed readily through the filters.

- During wear generation tests with filtration, the filters normally had to be exchanged several times because of excessive increase in pressure differential across the filter. Criterion for filter change was 6.2×10^5 Pa (90 psi) differential pressure. The 3 μm filters had to be changed more times during a test than the 15 μm filters. Possibly the filters were sized too small (not enough surface area) for hot-wall deposition testing with accelerated wear as performed in this program.

SECTION VI

RECOMMENDATIONS

The deleterious effects of mild steel wear and helpful effects of micronic filtration on turbine engine lubricant deposition certainly raises questions worthy of investigation. The fact that various lubricants, which undoubtedly have varying formulations, displayed different deposition and degradation characteristics would be of interest to lubricant formulators. A study to determine the effects of lubricant basestock and various lubricant additives on deposition is recommended. Metal deactivator, antioxidant, and load-carrying type additives would all be of interest.

In this program, significantly different friction torque requirements were noted for various lubricating oils. One oil repeatedly induced stalling of the wear-generator drive motor during testing while others did not, under the same testing conditions. On the other hand the oil that induced stalling (high friction between wear surfaces) also exhibited notably low wear. Therefore, it is recommended that a study be conducted whereby the test rig would be modified as necessary to measure friction in the evaluation of candidate lubricants. Again it would be of interest to evaluate specification approved lubricants as well as model lubricants to determine basestock and additive effects. Furthermore, since the current MIL-L-7808 specification contains no requirement for measurement of lubricant friction properties, the question arises as to what impact the parameter might have on engine/transmission operating efficiency. If there is a significant variance in the coefficient of friction between otherwise qualified lubricants, it is conceivable that measureable engine fuel cost benefits could accrue through the selection of low friction lubricants.

REFERENCES

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2. Cuellar, J.P., and Baber, B.B., "Hot-Wall Deposition Test Results on the Effect of Wear Metal," AFAPL Tech. Rept. 73-123, February 1974.

3. Baber, B.B., and Cuellar, J.P., "A Bearing Deposition Test for Evaluating Aircraft Gas Turbine Engine Lubricants," Lub. Engr., Vol. 25, March 1969.

4. Documented information obtained at AFWAL from P.W. Centers and H.A. Smith, at Project Review Meetings, October 1981 and March 1983.

5. Letter from P.W. Centers to L.J. DeBrohun, "Analysis of Lubricant Samples from Southwest Research Institute," dated 5 April 1983.

APPENDIX

TEST SUMMARY DATA FOR TEN LUBRICANTS

The following tables contain pertinent data for all ten of the lubricants employed in this program. A few tests that were questionable as to validity, were performed at other than "standardized test conditions, and/or were of an exploratory nature are not included in the tables.

Detailed test data sheets, with deposit specimen color photographs, from which these tables of data were derived were submitted to AFWAL for record with the monthly R&D Status Reports.

TABLE 7. HOT-WALL DEPOSITION TEST SUMMARY DATA FOR LUBRICANT O-72-13

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	24	41.0	10.7	0.56	--	882-3-2
None	None	30	46.0	10.5	0.58	--	884-3-3
None	None	30	48.0	10.4	0.56	--	885-4-2
None	None	23	48.0	9.9	0.60	--	887-4-2
1.171	None	24	90.5	13.8	0.98	--	886-3-3
1.189	None	23	91.0	12.1	0.94	--	888-3-3
1.078	None	23	90.0	11.9	0.84	--	889-4-2
1.007	None	18	88.0	10.2	0.71	--	904-3-5
None	15 μm	25	30.0	9.3	0.62	1(0)	913-3-9
None	15 μm	23	32.0	6.0	0.58	1(0.5)	914-4-10
1.582	15 μm	25	49.0	10.7	0.71	3(2.0)	915-3-9
1.478	15 μm	23	49.0	10.2	0.73	3(2.0)	916-4-7
None	3 μm	19	27.0	9.1	0.57	1(6.5)	898-3-5
None	3 μm	18	26.0	9.6	0.67	1(3.3)	900-3-5
1.450	3 μm	23	49.0	10.0	0.49	6(11.5)	917-3-9
1.481	3 μm	23	48.0	11.2	0.59	6(92.0)	918-4-7

TABLE 8. HOT-WALL DEPOSITION TEST SUMMARY DATA FOR LUBRICANT O-76-9

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	12	14.0	-0.1	1.92	--	890-3-3
None	None	19	14.0	1.5	1.94	--	891-4-6
None	None	20	13.5	1.4	2.08	--	893-4-6
0.653	None	17	46.5	3.4	7.16	--	894-3-5
0.592	None	18	61.0	6.2	7.94	--	897-4-6
0.864	None	16	48.5	3.5	6.65	--	908-3-7
0.741	None	21	55.5	2.8	6.55	--	909-3-9
None	15 μm	18	21.5	-0.2	1.60	1(2.5)	925-3-8
None	15 μm	18	17.5	0.3	1.44	1(0)	926-4-10
0.819	15 μm	19	46.0	5.5	6.20	2(0)	922-4-7
0.595	15 μm	22	39.5	5.2	6.74	2(2.0)	927-3-8
0.529	15 μm	17	27.5	5.5	6.31	1(46.0)	928-4-10
None	3 μm	15	21.5	-0.3	1.42	1(4.5)	923-3-8
None	3 μm	25	21.5	0.1	1.56	1(2.0)	929-3-8
0.879	3 μm	17	16.0	2.7	4.69	4(10.0)	930-4-10
1.287	3 μm	17	21.0	4.1	5.41	5(23.0)	942-4-10

TABLE 9. HOT-WALL DEPOSITION TEST SUMMARY DATA FOR LUBRICANT O-77-4

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final ∆ psi)	Test No.
None	None	21	24.5	3.2	0.56	--	977-3-16
None	None	16	30.5	2.0	0.98	--	978-4-19
None	None	26	28.5	4.0	0.81	--	1033-4-24*
None	None	32	37.0	5.4	1.39	--	1034-3-23**
1.725	None	21	61.0	3.5	1.02	--	979-3-16
1.707	None	19	55.5	1.4	0.97	--	980-4-19
1.513	None	21	52.0	3.3	0.75	--	993-3-20
None	15 μm	16	21.5	0.5	0.59	1(1.0)	989-3-20
None	15 μm	16	23.5	2.6	0.85	1(2.0)	990-4-19
1.802	15 μm	14	59.0	1.2	0.68	4(98.0)	987-3-20
1.815	15 μm	17	59.5	1.1	0.87	5(2.0)	988-4-19
1.114	15 μm	17	41.0	1.2	0.70	3(2.0)	996-4-19
None	3 μm	23	20.0	1.6	0.46	1(10.0)	991-3-20
None	3 μm	21	20.0	-3.5	0.33	1(10.0)	992-4-19
1.725	3 μm	17	51.5	1.7	0.57	8(71.0)	985-3-20
1.554	3 μm	19	48.0	3.9	0.59	10(7.0)	986-4-19
1.534	3 μm	19	41.0	2.6	0.43	9(11.0)	995-3-20

*Repeat test performed immediately prior to recalibration of temperature measuring system.

**Repeat test for verification purposes after recalibration of temperature measuring system. Hot-wall was equipped with two thermocouples to compare surface temperatures with heating-fluid temperature.

TABLE 10. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-78-9

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. of Filters (Final Δ psi)	Test No.
None	None	28	41.0	8.4	0.22	--	1026-3-23
None	None	24	40.0	8.1	0.25	--	1027-4-24
1.543	None	27	91.5	11.5	0.45	--	1019-4-23
0.624	None	34	89.5	9.9	0.41	--	1028-3-23
1.707	None	24	87.5	9.9	0.51	--	1029-4-24
None	15 μm	19	36.0	9.4	0.21	1 (8.0)	1025-4-24
None	15 μm	26	49.0	8.8	0.22	1 (9.0)	1031-4-24
1.543	15 μm	21	63.0	10.0	0.34	3 (18.0)	1022-3-24
None	3 μm	25	34.0	8.0	0.17	1 (0)	1023-4-23
None	3 μm	27	44.0	7.5	0.11	1 (2.0)	1030-3-23*
2.059	3 μm	32	67.0	11.1	0.30	6 (20.0)	1024-3-23

* Oil in sump was about 50°F low for approximately 15 hr at beginning of test.

TABLE 11. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-79-16

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr,%	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	22	27.0	8.4	0.28	--	901-4-6
None	None	16	27.0	8.2	0.23	--	912-4-9
1.232	None	24	54.5	9.6	0.54	--	907-4-8
1.591	None	17	56.0	9.6	0.48	--	910-4-10
1.378	None	26	60.5	8.8	0.44	--	911-3-10
None	15 μm	28	25.0	5.9	0.11	1(2.0)	931-3-8
None	15 μm	22	29.0	7.5	0.12	1(2.0)	932-4-10
1.713	15 μm	23	58.0	9.4	0.20	4(2.0)	938-4-10
1.550	15 μm	19	90.0	9.2	0.21	3(1.0)	941-3-14
1.970	15 μm	22	82.0	9.9	0.20	4(3.0)	944-4-10
None	3 μm	21	13.0	7.2	0.09	1(37.0)	934-4-10
None	3 μm	18	33.0	7.8	0.19	1(2.0)	943-3-16
1.655	3 μm	23	49.0	8.2	0.23	5(100.0)	939-3-13
1.759	3 μm	20	48.0	9.7	0.22	7(34.0)	940-4-10

TABLE 12. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT 0-79-17

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	20	40.0	14.0	0.46	--	945-3-16
None	None	26	41.0	15.5	0.48	--	946-4-10
1.888	None	19	102.0	18.0	0.64	--	947-3-16
2.094	None	22	98.5	15.7	0.64	--	948-4-10
None	15 μm	28	35.0	14.4	0.53	1(2.0)	956-4-10
None	15 μm	25	31.0	14.9	0.44	1(3.0)	963-3-16
2.085	15 μm	25	87.5	17.1	0.56	5(2.0)	954-4-10
1.987	15 μm	21	91.5	17.2	0.65	4(3.0)	955-3-16
None	3 μm	22	25.0	15.5	0.45	1(5.0)	957-3-16
None	3 μm	22	22.0	14.6	0.53	1(2.0)	958-4-17
2.020	3 μm	25	83.5	17.0	0.56	9(5.0)	952-4-10
1.884	3 μm	21	87.5	18.9	0.58	7(23.0)	953-3-16

TABLE 13. HOT-WALL DEPOSITION TEST SUMMARY DATA FOR LUBRICANT 0-79-20

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final psi)	Test No.
None	None	26	33.0	7.5	0.29	--	967-3-16
None	None	21	30.0	6.3	0.24	--	968-4-17
None	None	22	35.0	7.6	0.33	--	971-3-16
1.642	None	22	119.0	8.6	0.64	--	969-3-16
2.235	None	20	119.5	8.6	0.71	--	970-4-17
1.732	None	29	94.0	9.1	0.68	--	974-4-17
None	15 μm	26	31.0	6.7	0.35	1(2.0)	972-4-17
None	15 μm	23	32.0	6.9	0.38	1(1.0)	973-3-16
1.726	15 μm	24	87.0	8.3	0.39	4(1.0)	959-3-16
1.883	15 μm	24	81.0	8.7	0.37	4(69.0)	960-4-17
None	3 μm	19	27.0	5.2	0.27	1(1.0)	965-3-16
None	3 μm	22	24.0	7.6	0.27	1(2.0)	966-4-17
1.638	3 μm	22	49.0	8.4	0.44	7(59.0)	961-3-16
1.808	3 μm	18	49.0	8.8	0.39	9(20.0)	962-4-17

TABLE 14. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-82-2

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	26	22.0	6.6	1.24	--	997-3-20
None	None	22	22.0	7.3	1.49	--	998-4-19
None	None	31	18.0	10.0	2.65	--	1055-4-26
1.661	None	19	67.5	8.2	1.43	--	999-3-20
1.571	None	19	66.0	8.0	1.49	--	1004-4-19
None	15 μm	23	26.0	7.5	1.23	1 (1.0)	1001-3-20
None	15 μm	26	17.0	7.1	1.23	1 (0)	1003-3-20
None	15 μm	22	27.0	6.9	1.05	1 (0)	1008-4-22
1.863	15 μm	23	47.0	8.4	1.29	4 (1.0)	1006-4-22
None	3 μm	23	22.0	7.3	1.34	1 (0)	1002-4-19
None	3 μm	17	20.0	7.3	1.46	1 (0)	1007-3-21
1.405	3 μm	21	46.0	7.4	1.10	6 (2.0)	1005-3-21

Test Parameters					Test Results		
Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	[illegible] Vis Inc.,	NN Change, mg KOH/g	No Filters (Final [illegible] psi)	Test No.
None	None	20	21.0	11.0	0.35	--	1009-3-21
None	None	23	20.0	12.2	0.47	--	1010-4-22
None	None	22	10.0	11.5	0.46	--	1020-3-24
None	None	22	12.0	13.7	0.60	--	1035-4-24*
1.557	None	25	61.5	14.9	0.91	--	1015-3-21
1.889	None	23	69.5	31.3	3.21	--	1016-4-23
None	15 μm	19	10.0	11.2	0.46	1(1.0)	1012-4-22
None	15 μm	26	10.0	10.6	0.46	1(2.0)	1018-3-21
1.041	15 μm	18	14.0	15.1	0.67	2(0)	1014-4-22
None	3 μm	19	10.0	11.0	0.44	1(10.0)	1011-3-21
None	3 μm	23	11.0	11.6	0.63	1(8.0)	1017-3-21
1.362	3 μm	22	14.0	17.0	0.90	3(76.0)	1013-3-21

*Repeat test for verification purposes after recalibration of temperature measuring system. Hot-wall was equipped with two thermocouples to compare surface temperatures with heating-fluid temperature. One thermocouple became *inoperative during test*.

TABLE 16. HOT-WALL DEPOSITION TEST SUMMARY DATA
FOR LUBRICANT O-82-14

Test Parameters			Test Results				
Total Wear, g	Filter	Specimen Drain, ml/min	Deposit Rating	40°C Vis Incr, %	NN Change, mg KOH/g	No. Filters (Final Δ psi)	Test No.
None	None	25	31.0	9.4	0.88	--	1044-3-25
None	None	33	49.0	10.3	0.80	--	1047-4-26
None	None	22	32.0	9.2	0.71	--	1052-3-25
2.040	None	24	103.0	12.3	1.66	--	1046-3-25
1.807	None	26	79.5	12.7	1.49	--	1049-4-26
2.068	None	27	80.5	12.6	1.48	--	1053-4-26
None	15 μm	25	35.0	12.3	0.93	1(0)	1042-3-25
None	15 μm	24	30.0	10.5	0.89	1(0)	1050-3-25
1.329	15 μm	24	52.0	11.3	1.23	4(3.0)	1040-3-25
1.698	15 μm	31	56.5	13.0	1.31	6(2.0)	1041-4-26
None	3 μm	25	46.0	9.8	0.87	1(16.0)	1048-3-25
None	3 μm	29	31.0	10.4	0.90	1(18.0)	1051-4-26
1.599	3 μm	27	66.0	10.6	1.08	6(18.0)	1038-3-25
1.773	3 μm	33	95.5	12.5	1.17	11(17.0)	1039-4-26
1.724	3 μm	31	81.0	12.9	1.11	12(0)	1043-4-26

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